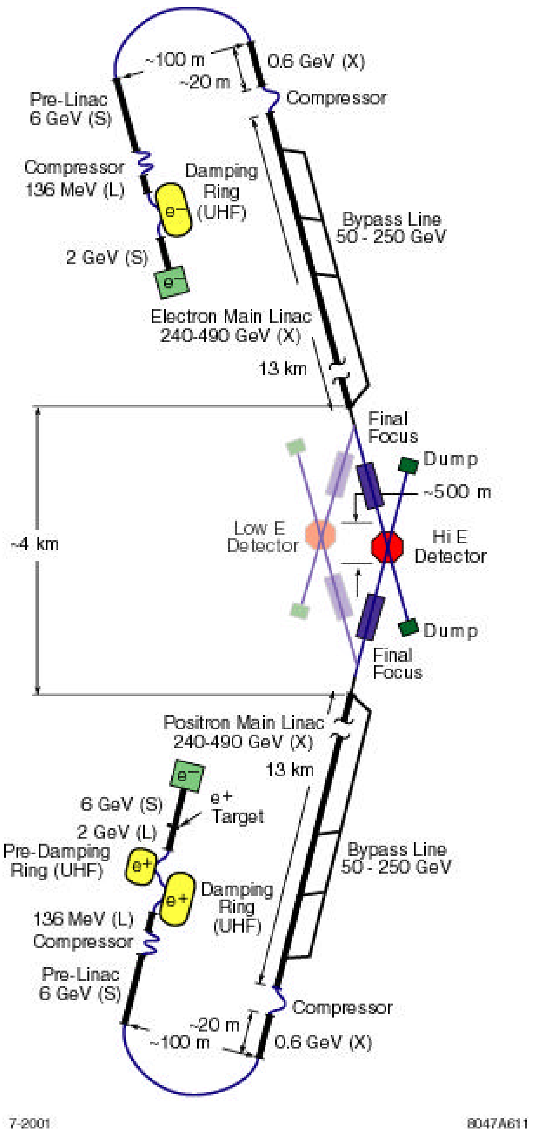


NLC Design and Development

FNAL
March 28th, 2002

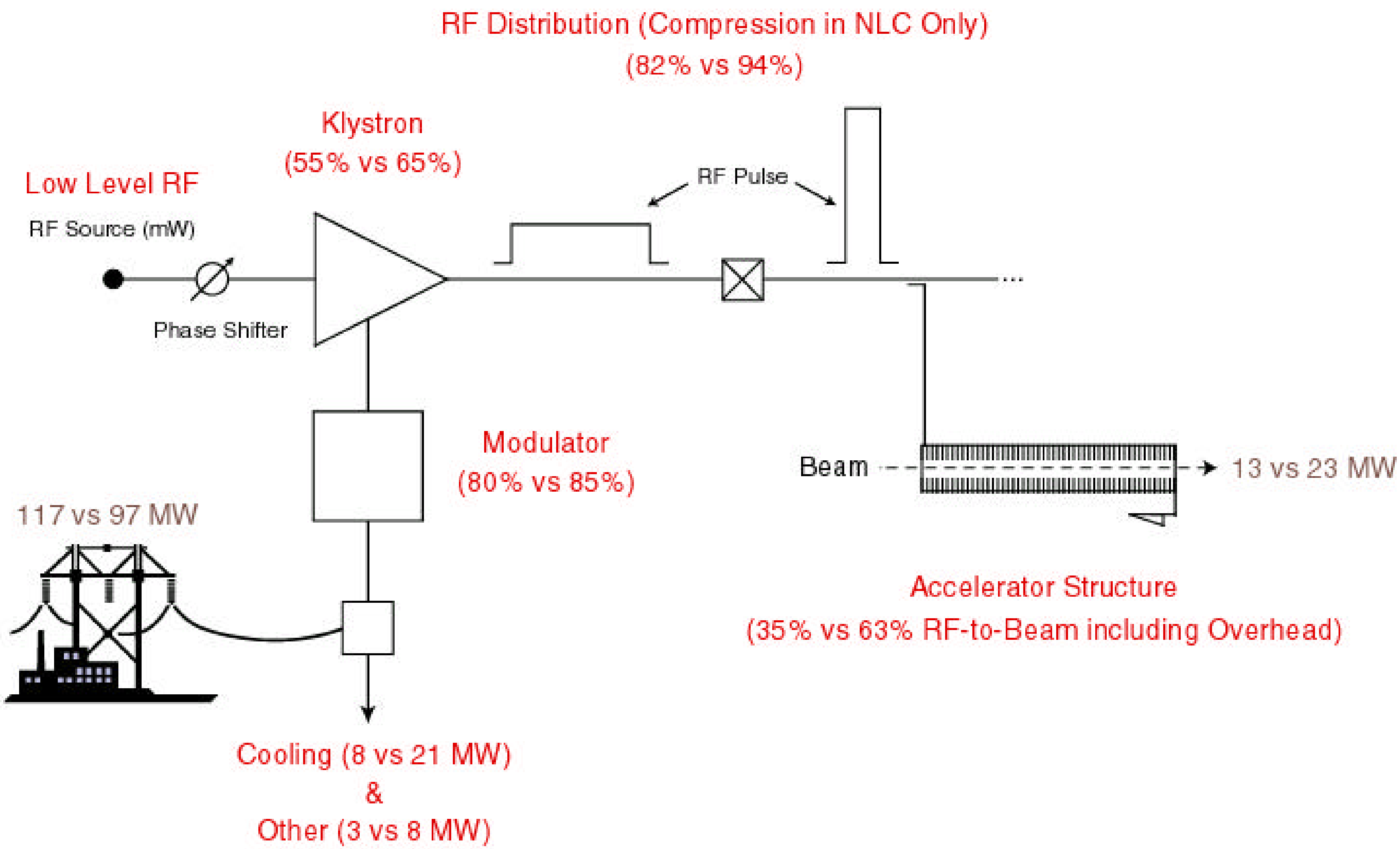
Tor Raubenheimer

SLAC

Outline

- Two issues for LC: energy and luminosity
- RF systems
  - Modulators, klystrons, cavities and test facilities
- Luminosity issues
  - Parameters
  - Damping rings and sources
  - Main linac dynamics and alignment
  - Beam delivery systems
  - IP issues

RF Schematic



X-Band RF System

NLCTA RF system (ZDR, 1996):

- Conventional PFN modulator (500 kV, 500 A, 1.5 μs)
- 50 MW / 1.5μs solenoid-focused klystrons
- SLED-II pulse compression
- DDS structures work at gradients up to 45 MV/m

→ Tested, could be used to build a 500 GeV collider

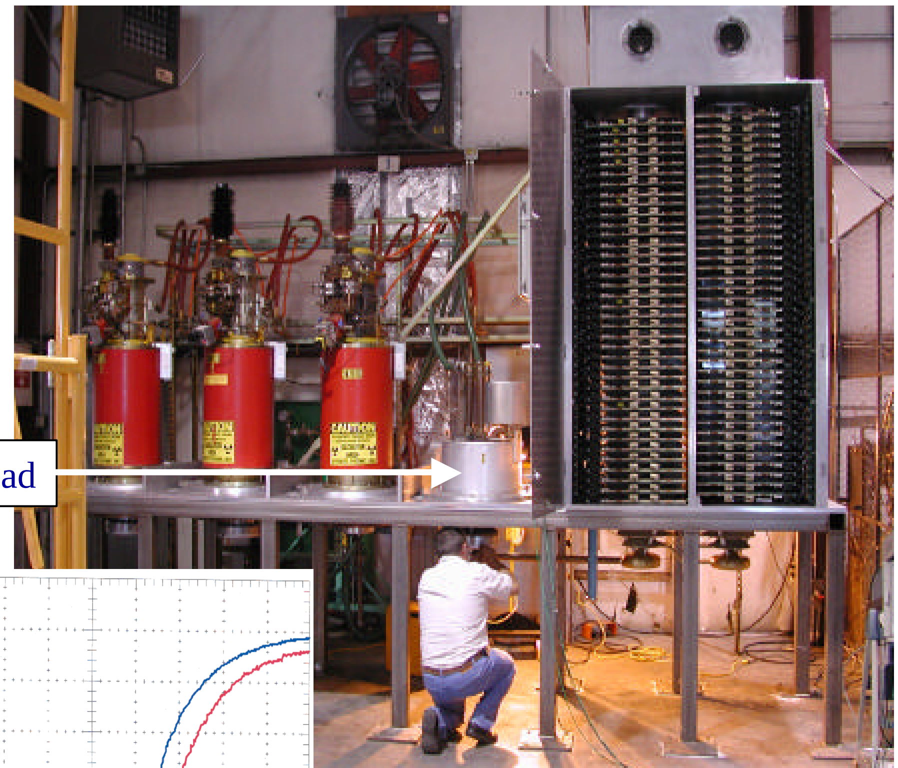
Improvements to reduce cost and improve performance:

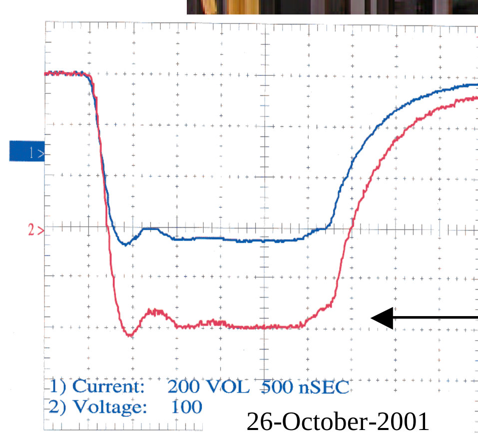
- Solid state modulator (500 kV, 2000 A, 3 μs)
- 75 MW / 3μs PPM-focused klystrons
- DLDS pulse compression
- RDDS structures - 70 MV/m

→ Aimed to optimize performance and cost at 1 TeV

Modulators

- Both NLC and TESLA have modulator designs based on solid state IGBT's
- Switch MW's of power and deliver lots of energy
  - NLC: 500 kV, 2000 A, 3.1 μs
  - TESLA: 12 kV, 1600 A, 1.7 ms
- NLC prototype solid state modulator testing started in October
- Problems with IGBT damage being solved





NLC Klystrons

- Over 14 X-band klystrons built and operated
  - XL4's are work horse for NLCTA and other test stands (many tubes with 10 ~ 20,000 hours)
- Periodic Permanent Magnet (PPM) for increased efficiency

Present goal: 75 MW with 3 μs pulse width at 120 Hz or greater

XP3 results look good

Recent success at KEK with 75 MW and 1.5 μs looks good

	Focusing	Peak Power	Pulse length	Rep. rate
XL4	**Solenoidal**	**50 MW**	**1.5 us**	**120 Hz**
10 tubes @ 10,000 hrs.		50 MW	1.5 us	120 Hz
		75 MW	1.5 us	120 Hz
		50 MW	2.4 us	120 Hz
X5011	**PPM**	**50 MW**	**1.5 us**	**60 Hz**
1 tube (1996)		60 MW	1.5 us	60 Hz
		50 MW	2.4 us	60 Hz
XP1	**PPM**	**75 MW**	**1.5 us**	**No cooling**
1 tube (2000)		75 MW	3.1 us	
		90 MW	0.5 us	
XP3	**PPM**	**75 MW**	**3.2 us**	**60 Hz**
Tests started 2/02:	DC	480 kV	3.2 us	60 Hz
	RF	75 MW	2.8 us	10 Hz

Energy: RF Distribution

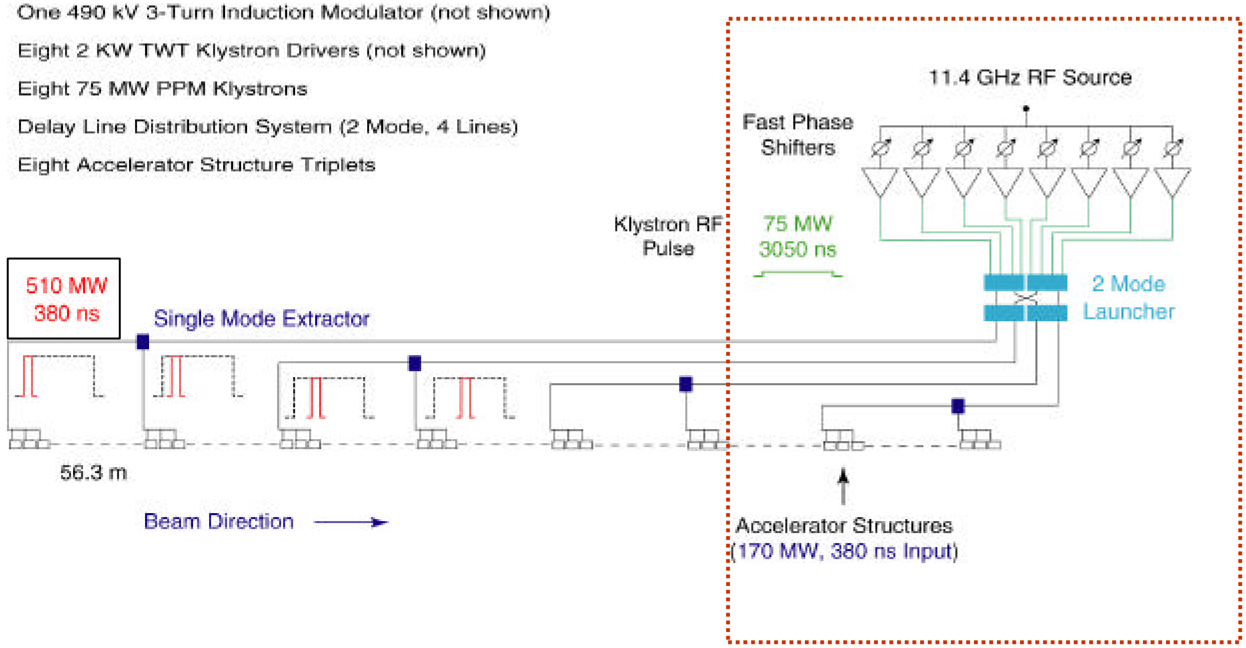
- Delay Line Distribution System (DLDS)
  - Complicated rf components to exchange modes and direct power
  - Massive vacuum system
  - Completely passive rf switching
  - Next step: validate rf power handling (600 MW in 400 ns)
  - Systems tests in 2003 and 2004

- SLED-II – previous pulse compression system
  - Less efficient than DLDS (65% instead of 85%)
  - Many similar power handling issues
  - Maximum power tested thus far is 500 MW at 150 ns and 400 MW at 240 ns
  - Operating on NLCTA since 1996

NLC RF System Tests

NLC Linac RF Unit

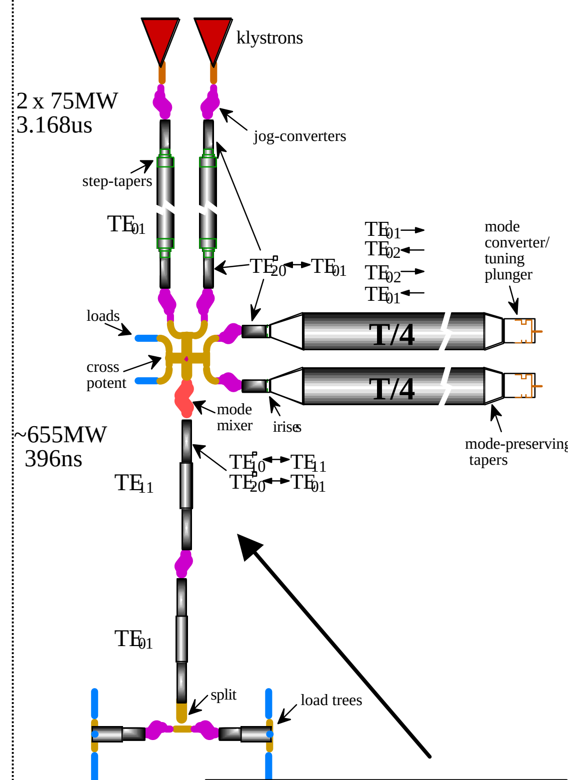
Low Level RF System
One 490 kV 3-Turn Induction Modulator (not shown)
Eight 2 KW TWT Klystron Drivers (not shown)
Eight 75 MW PPM Klystrons
Delay Line Distribution System (2 Mode, 4 Lines)
Eight Accelerator Structure Triplets



Full "8-Pack"
NLCTA end of 2003
Modulator; klystrons;
¼ DLDS; 12 structures

"Single-Feed"
Intermediate Step
Fall 2002

Multi-Moded SLED-II

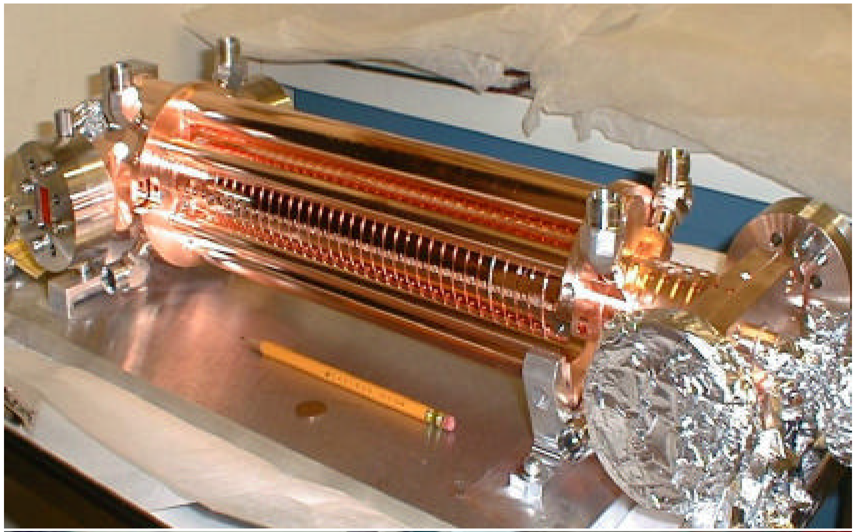


650 MW in 400 ns

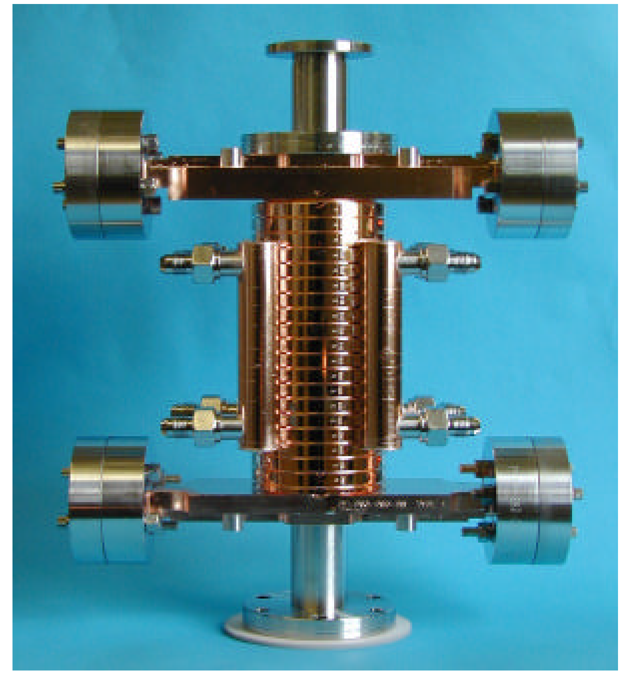
NC Accelerator Structures

- Not near gradient limits for copper
  - Single cell cavities hold gradients of ~ 200 MV/m
  - 'Short' structures processed rapidly to >100 MV/m
- Built many 1.3-m ~ 1.8-m structures
  - Meet fabrication tolerances
  - Studied wakefield damping extensively – damping sufficient although not at desired values due to trivial errors, solutions in-hand
  - Stable operation limited to 40 ~ 45 MV/m
- Processing model – increase voltage until breakdown
  - Not strongly coupled to cleanliness - different than SC models
  - Small arcs clean surface / large arcs damage surface
  - Difference between the two is how much energy is deposited → low vg
  - Some 'damage' is acceptable however need to extrapolate out 10~20 years
  - Other models predict constant damage – inconsistent with single cell data

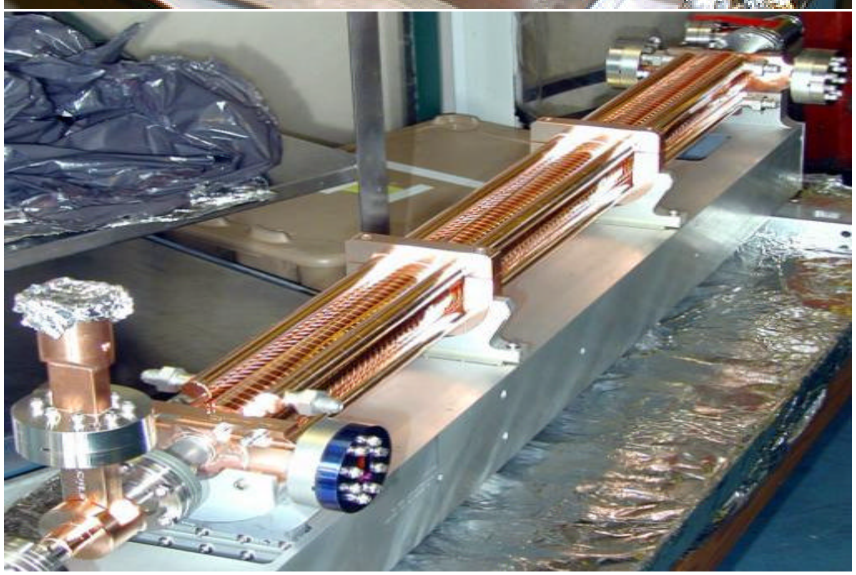
Low Group Velocity Test Structures



DS2S
52 cells DS2



20 cm test
5% to 4% v_g



105 cm test
5% to 1% v_g

Built 9 traveling wave test structures

Rapid processing to >70 MV/m

DS2S 1500 hrs @ 50-70 MV/m

Vg 5% 500 hrs @ 65-75 MV/m

Two subsequent traveling wave structures operated at 70 MV/m with peak 85 MV/m

Gradient Issues

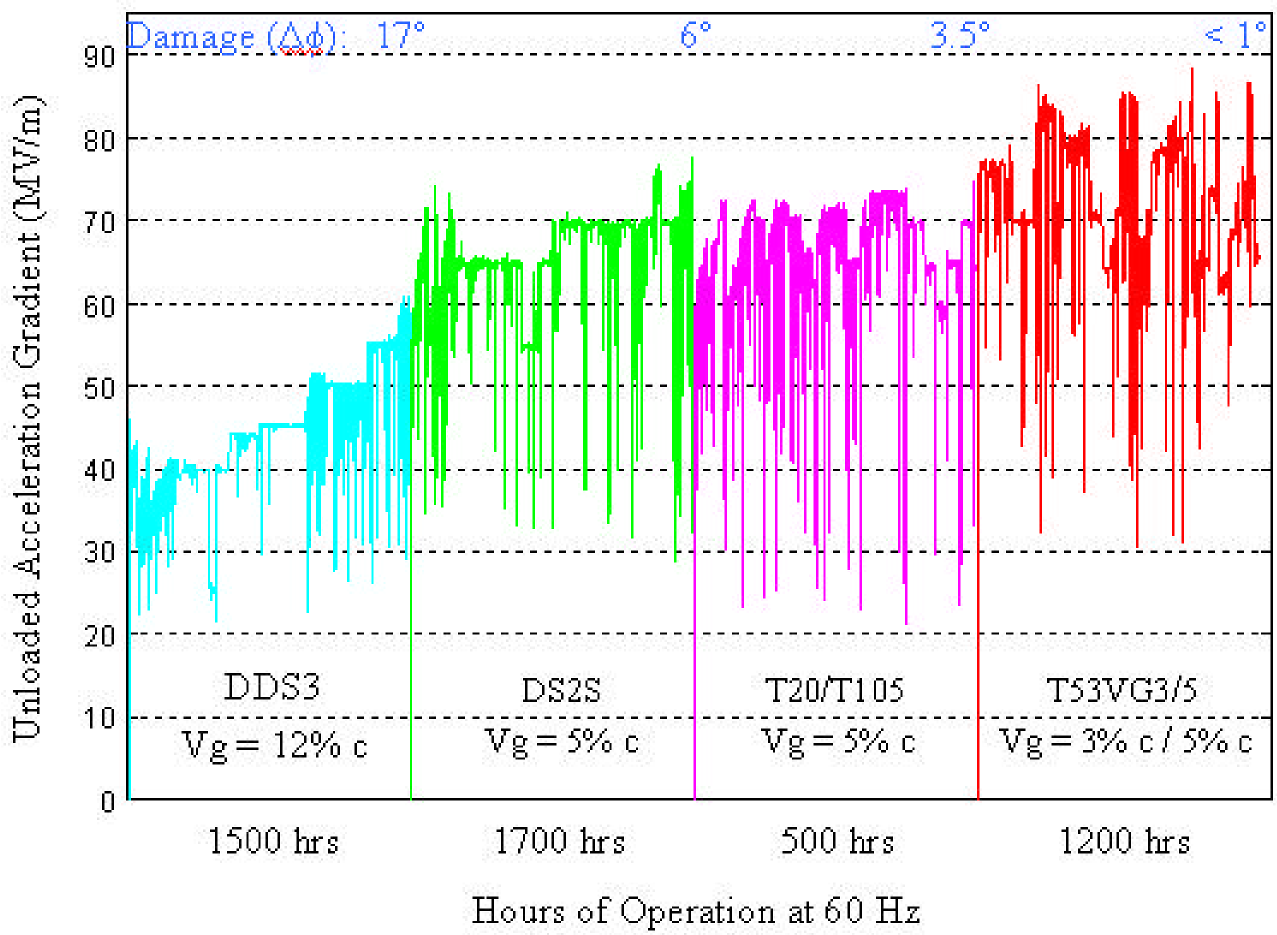
- Low group velocity structures rapidly process to ~70 MV/m

- Small damage during initial processing seen with beam

- Minimal damage during subsequent operation

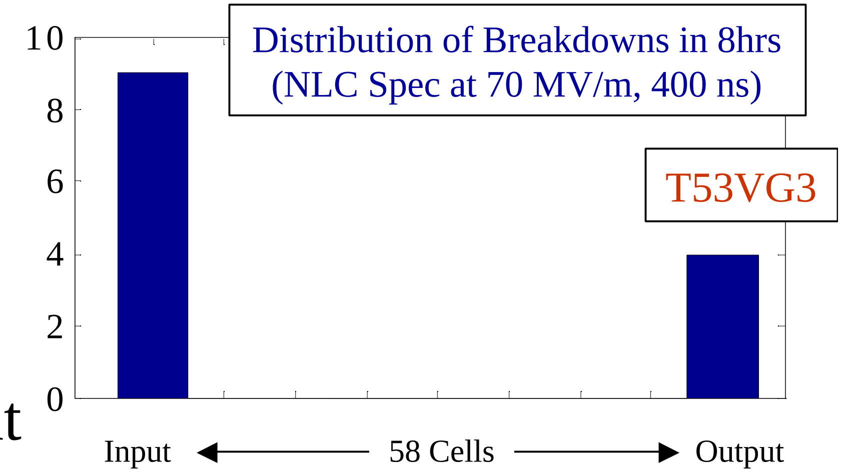
- Breakdown rate is few per hour, i.e. few per 200,000 pulses

Operation History of Six Test Structures



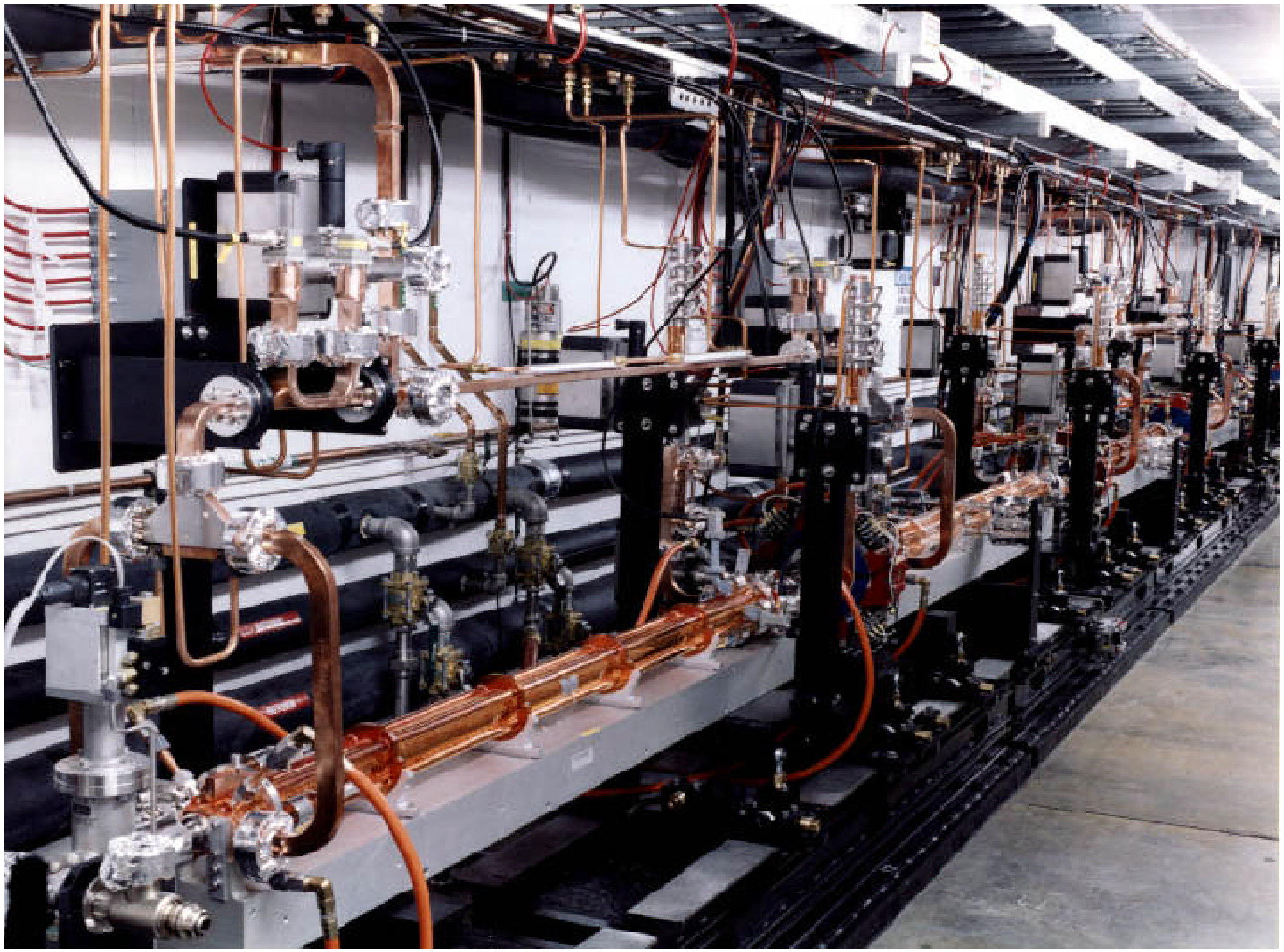
NLC Accelerator Structures

- Built many test structures to study gradient limitation
  - Much better performance with low vg than original NLC design
  - Peak gradients of 80 to 90 MV/m and operate at 65 to 75 MV/m
  - Trip rates look OK
  - Damage looks OK



- Next step: combine NLC-style wakefield control with high gradient
  - Demonstrated single and multi-bunch wakefield control in 1.8-m structures
  - Building two pairs of ‘NLC’ style structures with single bunch wakefield control and detuning for long-range wakefield
    - first pair with normal couplers and the second with in-line tapered couplers to reduce Es at the input and output couplers
  - Will test NLC structures with both single and multi-bunch wakefield control by the end of 2002

NLC Test Accelerator



Operated since 1996

5000 hrs just this year

Essentially NLC-500 rf system from 1996:

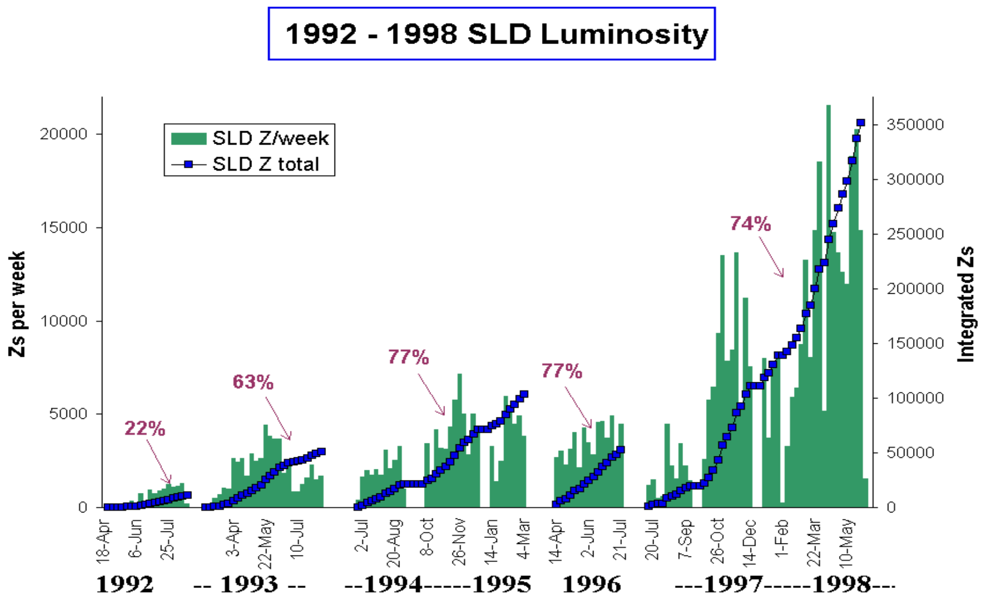
- Dual 50MW klystrons
- SLED-II
- 1.8 m long structures

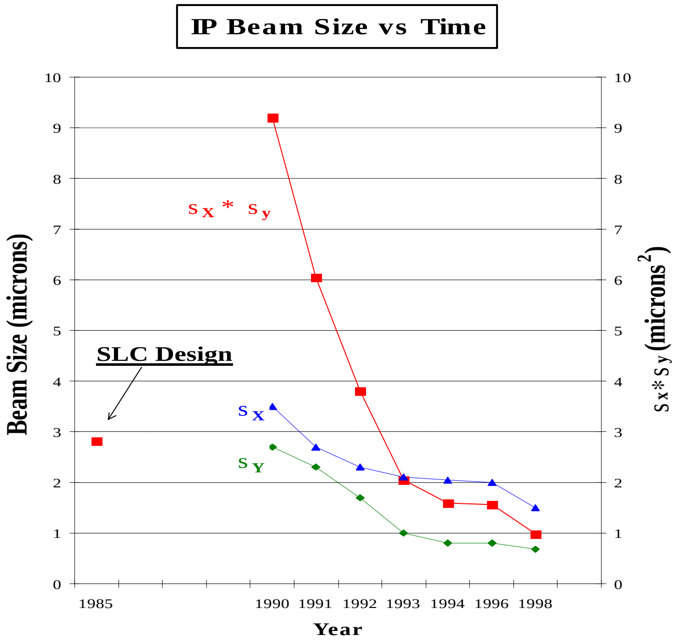
2001 JLC/NLC Parameters

	Stage 1		Stage 2	
CMS Energy (GeV)	500		1000	
Site	US	Japan	US	Japan
Luminosity (10^{33})	**20**	**25**	**30**	**25**
Repetition Rate (Hz)	120	150	120	100
Bunch Charge (10^{10})	**0.75**		**0.75**	
Bunches/RF Pulse	192		192	
Bunch Separation (ns)	1.4		1.4	
Eff. Gradient (MV/m)	**48.5**		**48.5**	
Injected $\gamma\varepsilon_X$ / $\gamma\varepsilon_Y$ (10^{-8})	300 / 2		300 / 2	
$\gamma\varepsilon_X$ at IP (10^{-8} m-rad)	360		360	
ge$_y$ at IP (10^{-8} m-rad)	**4**		**4**	
β_X / β_Y at IP (mm)	8 / 0.11		13 / 0.11	
s$_x$ / s$_y$ at IP (nm)	**243 / 3.0**		**219 / 2.3**	
q$_x$ / q$_y$ at IP (nm)	**32 / 28**		**17 / 20**	
σ_Z at IP (um)	110		110	
Υ_{ave}	0.14		0.29	
Pinch Enhancement	1.51		1.47	
Beamstrahlung δB (%)	5.4		8.9	
Photons per e+/e-	1.3		1.3	
Two Linac Length (km)	12.6		25.8	

- High current parameters
- Additional parameters with slightly lower charge 0.65×10^{10} and smaller beta functions for similar luminosity
- Low energy parameters also exist for operation at the Z, W, low-mass Higgs, and top

Luminosity: Building on the SLC





New Territory in Accelerator Design and Operation

- Extensive feedback & online modeling
- Correction techniques expanded from first-order (trajectory) to include second-order (emittance), and from hands-on by operators to fully automated control

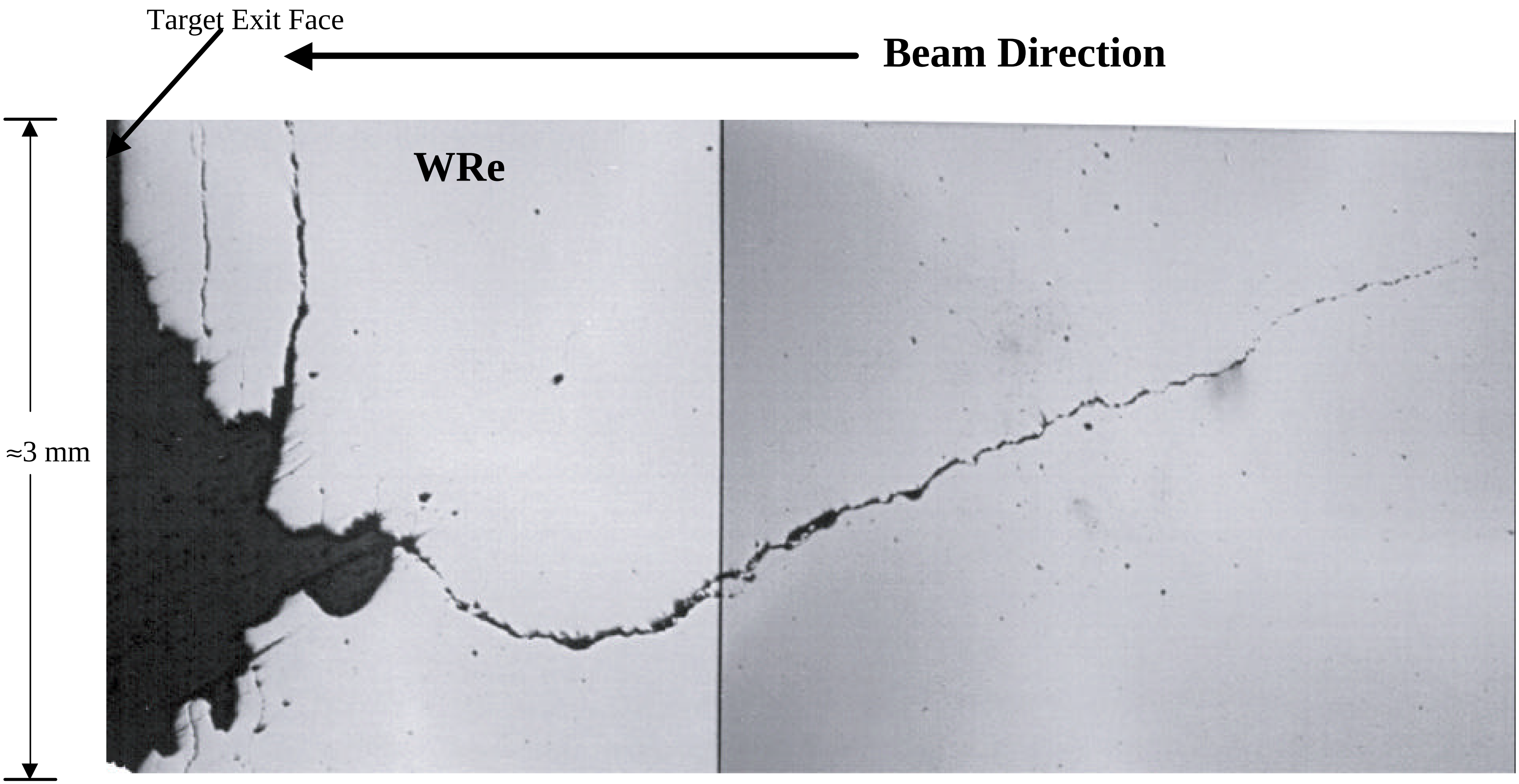
"It's the diagnostics, stupid"

"The damping rings are the source of all evil"

Electron and Positron Sources

- Both are based on 'conventional' sources used at the SLC
- Polarized electron source had limitation due to 'Surface Charge Limit'
  - Electrons would be trapped at the surface generating a potential barrier for further electrons
  - Problem has been solved by varying the doping with depth
  - Laser system is not commercially available but should be possible
- SLC positron target was damaged at end of the SLC run
  - Diagnostics at LANL and modeling at LLNL
  - Design with 3 interleaved targets for robust design
  - Also looking at TESLA-style undulator-based system
    - Need a number of modifications to make system robust

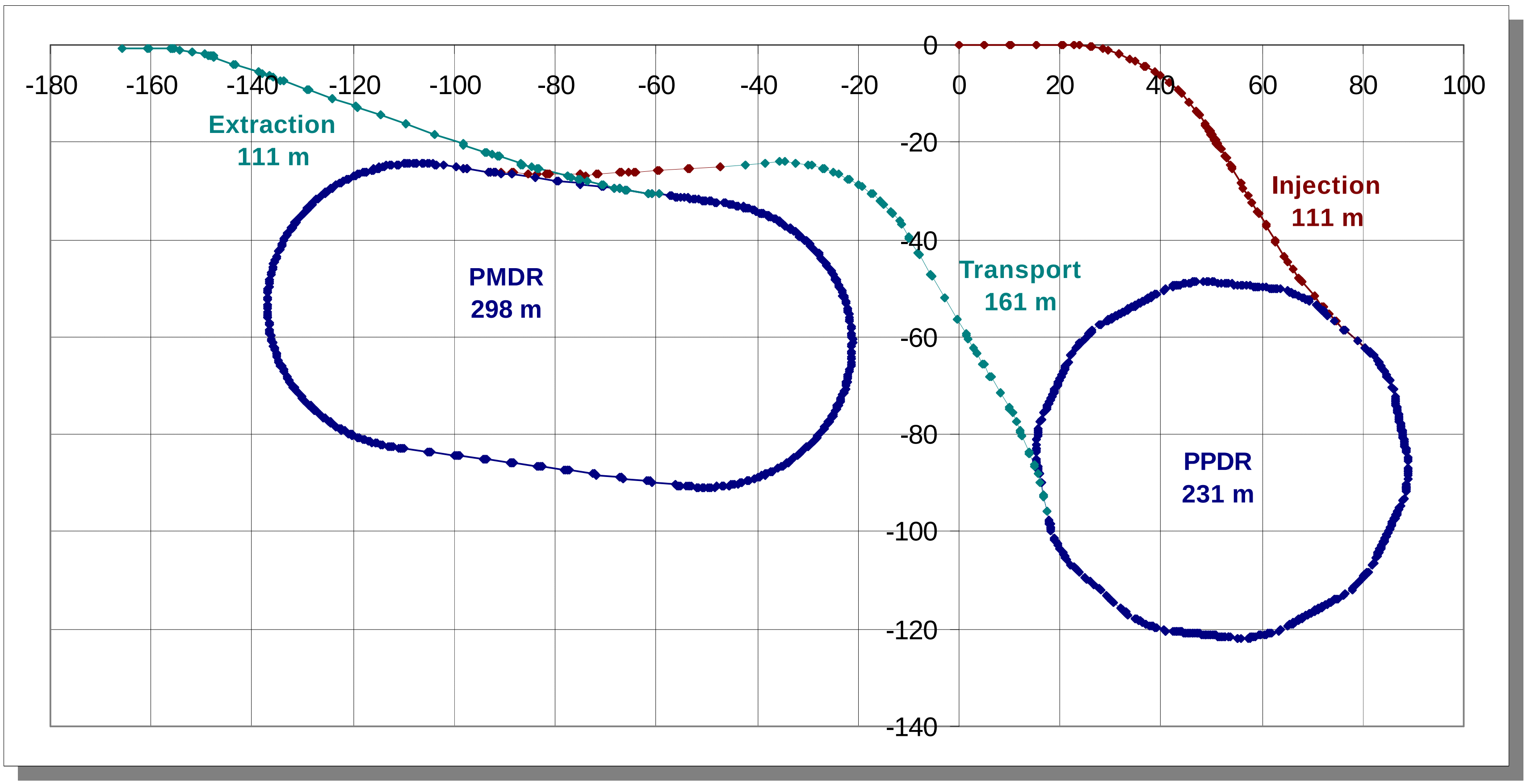
SLAC Positron Target



Damping Rings

NLC rings are similar to present generation of light sources (similar energies, emittances, sizes, and currents)

Damping rings probably have most complex acc. physics issues



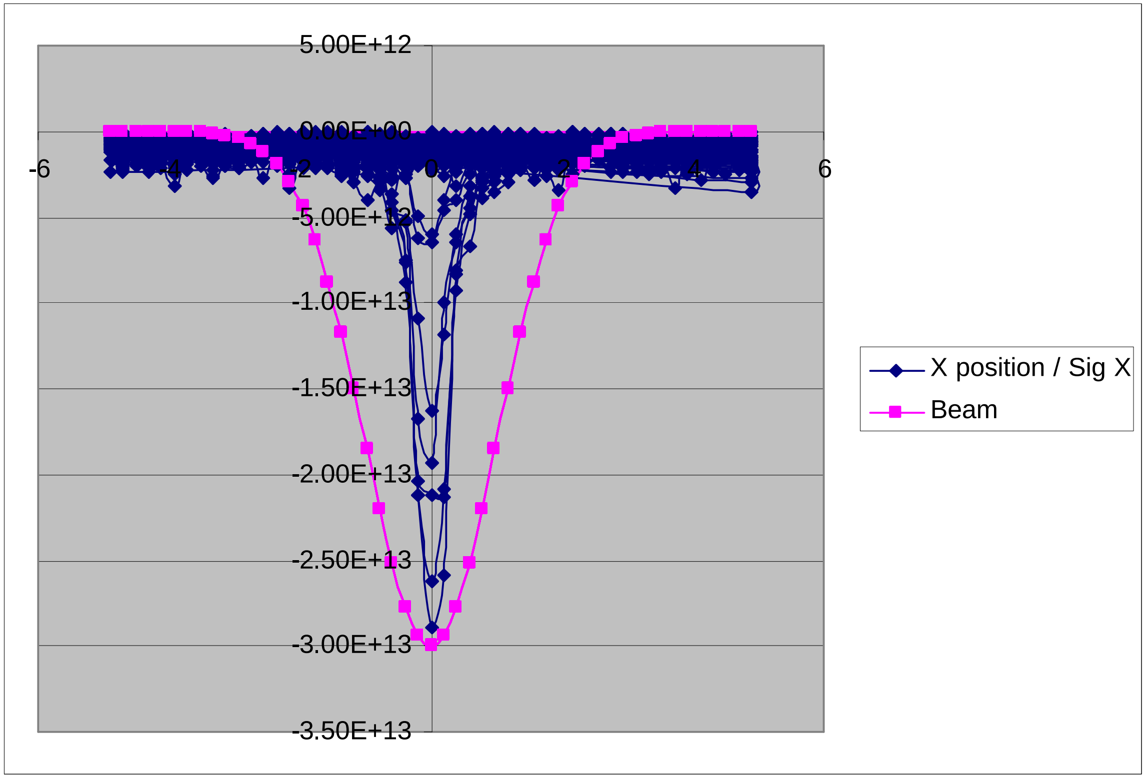
Damping Ring Issues

- Achieving the vertical emittance (~ 0.5% coupling ratio) requires much better alignment than typically in storage rings
- Incoherent space charge tune shift is ~ 0.05!
- Intrabeam scattering becomes significant with high densities
- Touschek lifetime is roughly 1 minute
- Old instabilities:
  - Microwave – bursting instability has huge effect downstream
  - Transient loading – impacts bunch compressor designs
  - Coupled bunch – need feedback with very high power but low noise in transverse and longitudinal
- New instabilities:
  - Electron cloud – initial simulations show tune spreads ~1
  - Ions – fast coupled bunch growth rates with few solutions

Tune Spreads in Beams

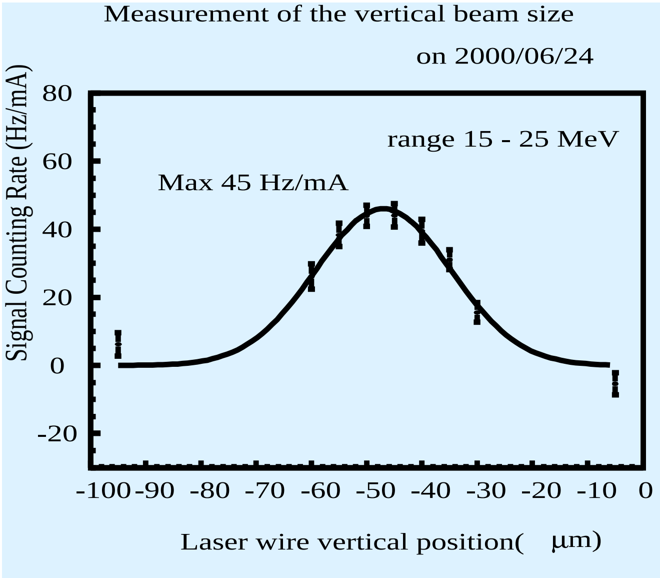
- Concerns about control of vertical emittance
- Estimates for NLC and TESLA predict electron cloud induced incoherent tunes spreads of 0.30 and 8, respectively
- Estimates predict ion induced tunes spreads of 0.01 and 0.06 in NLC and TESLA
  - This is bad enough!

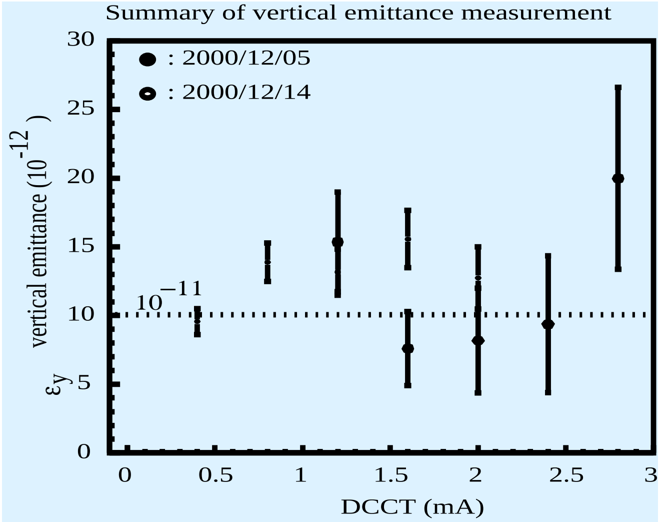
Cloud density in beam



ATF Damping Ring at KEK

Vertical emittance $3.5x10^{-8}$ measured with laser wire (~2 x NLC spec)





Linac Dynamics

- Two separate issues: Beam BreakUp (BBU) and 'static' alignment or emittance dilutions
  - BBU quasi-exponential amplification of incoming trajectory errors
    - Well understood and well simulated!
    - Multi-bunch BBU seen in 60's in SLAC linac
    - Single bunch BBU solved in SLC in mid-80's
    - Need to measure/model wakefields
  - Quasi-static emittance dilutions
    - Cavity alignment
    - Magnet alignment
    - Rf deflections
    - Stray fields
    - Use beam-based alignment!
    - Techniques developed and tested at SLC, FFTB, ASSET, and elsewhere!

BBU: Wakefield Summary

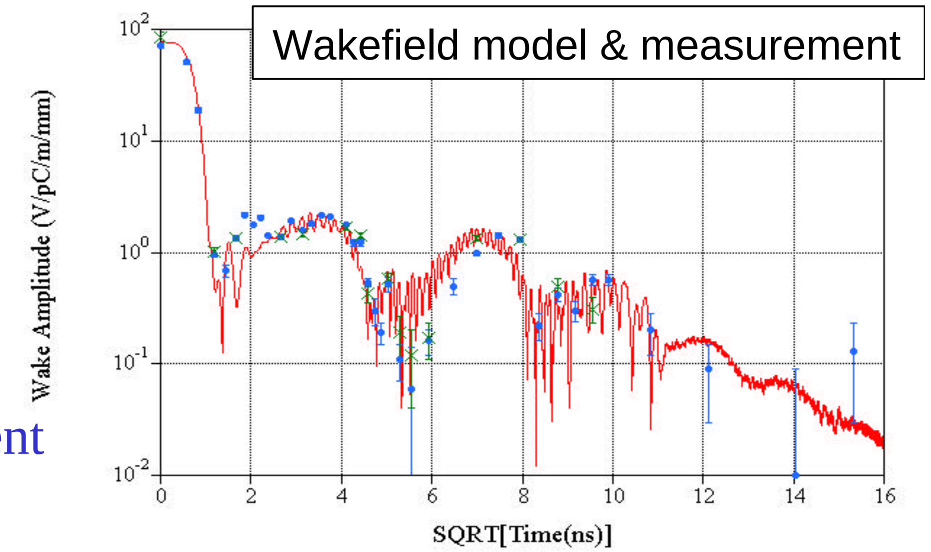
- Wakefields have been measured the ASSET facility at SLAC and the TTF at DESY using beam
  - Wakefields are larger than design although sufficient
  - In last three NLC structures, errors were due to known construction errors while at DESY they due to a miscalculation:
    - DDS1: a 50 um offset arose when bonding 25 cm lengths
    - DDS3: a set of cells were manufactured with 10 MHz frequency error
    - RDDS1: differential expansion of ceramic/copper at ends when diffusion bonding and again when bonding stainless vacuum manifold
- Long-range wakefield is no longer thought to be a limiting problem but must be careful in design and fabrication!
  - Devil is in the details!
- Both LC’s aims to measure high gradient cavities in 1 yr
- Working on wire measurement to rapidly qualify structures

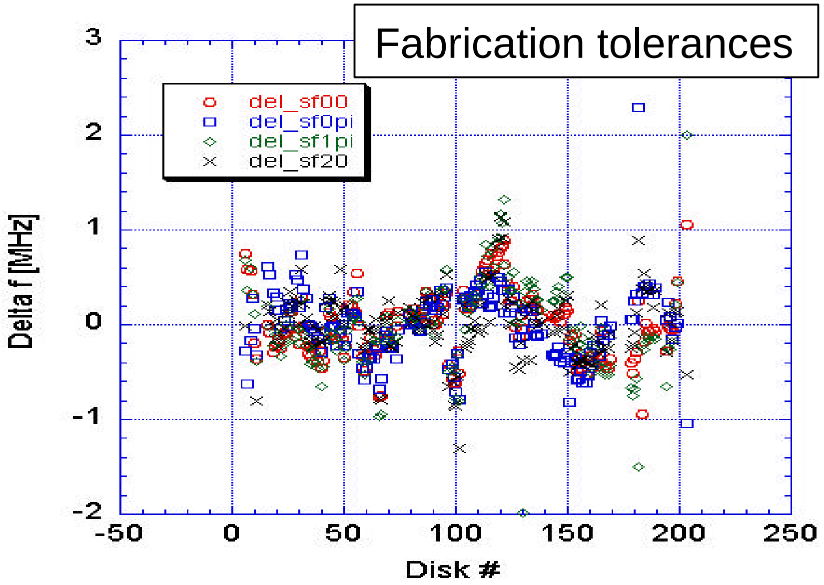
Structure Design Issues

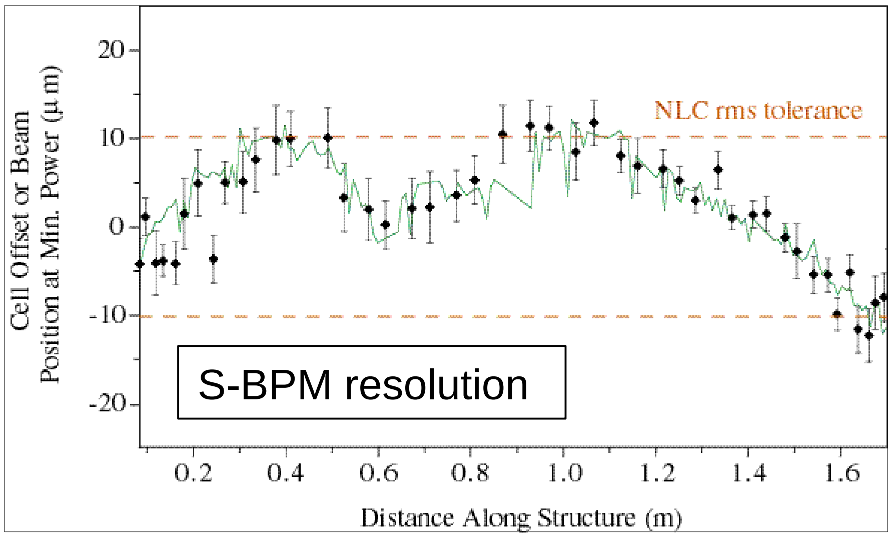
Precision wakefield measurements agree well with model prediction

Fabrication achieved frequency errors 0.5 MHz rms (tolerance 3 MHz)

Structure BPM achieved < 1 μm centroid resolution (tol. 20 μm) – essential for alignment







Beam-Based Alignment (e Tuning)

- To preserve emittance must correct **net** effect of individual dilution sources
- ‘Local’ correction - directly correct dilution sources
  - Beam-based alignment – tested SLC; FFTB; other beam lines
  - Most robust solution / least sensitive to energy or strength errors
- ‘Quasi-Local’ correction - correct dilution effects over short distance, i.e. betatron wavelength
  - Dispersion-Free steering – tested in SLC; LEP; other rings
  - Based on ‘measurements’ of dilution / sensitive to systematics
- ‘Global’ correction - tune emittance using direct ε diagnostics
  - Directly corrects desired quantity / sensitive to phase advance – tested SLC

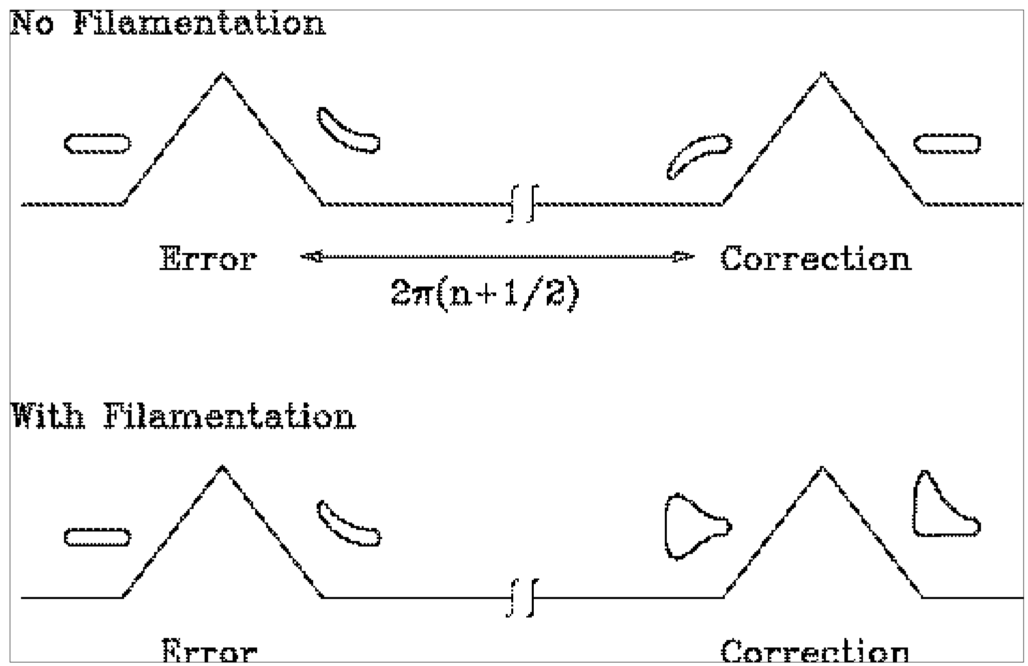
Emittance Correction (Global Correction)

- Most sources of emittance dilution come from conservative processes: transverse wakefields, dispersive errors, etc.

$\Rightarrow$6-D phase space *does not* increase
(only the projected phase space increases)

- Any conservative dilution can be removed but this is difficult after phase space mixing from betatron frequency variations

- Filamentation is significant in NLC



Alignment Tolerances

- Alignment tolerances in NLC/JLC are very tight!
  - 1 - 10 μm in the main linacs and similar in the final focus
- Lesson from SLC: diagnostics and control
  - Want 300 nm Beam Position Monitor resolution
    - FFTB/SLC FF striplines have 1 μm resolution
    - FFTB RF cavity BPM had 40 nm resolution
  - Want beam size resolution of 300 nm
    - SLC laser wire had between 500 and 230 nm resolution
    - FFTB 'Shintake' BSM had 40 nm resolution
  - Want magnet movers with 50 nm step size
    - FFTB magnet movers have 300 nm step sizes
- With sufficient diagnostics and controls - accelerator becomes big feedback loop but easy to diagonalize
- Stability very important for convergence!

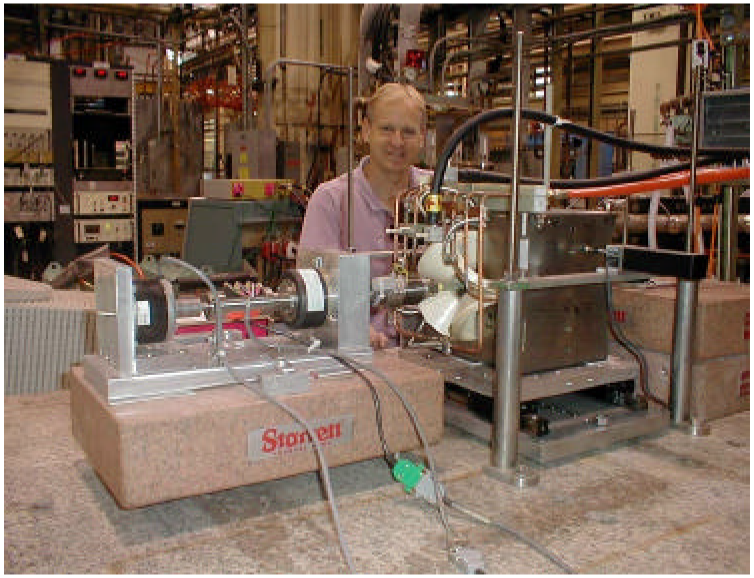
Rf Cavity Alignment

- NLC structures (cavities) must be aligned to beam within 10 μm rms for 20% $\Delta\varepsilon$
  - Every structure has two rf-BPMs with better than 2 μm accuracy
  - Short-range wakefields depend on average of structure offset
  - Average position of the 6 structures on an rf girder and move girder end-points with remotely controlled movers

- TESLA cavities must be aligned with 500 μm rms for 15% $\Delta\varepsilon$
  - Achieved +/- 250 μm alignment within cryostat
  - But effects add → tolerance for 12 cavities in cryostat ~ 140 μm
  - Effect is worst at $\frac{1}{4}\lambda_\beta$ = 150 m → tolerance for cryostats ~ 45 μm
  - Either add read-backs on HOM dampers and steer beam to center of cavities or use global emittance bumps like those used in SLC to cancel dilutions
  - RF deflections imposes 100 μrad tolerance on cavities for 5% $\Delta\varepsilon$

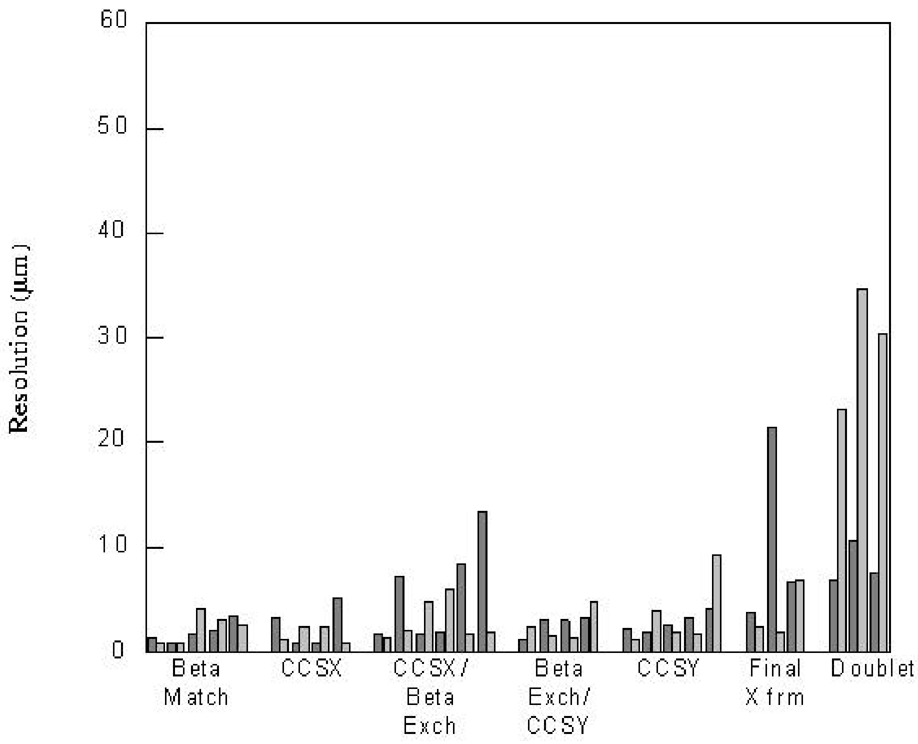
Quadrupole Alignment

- Quadrupoles must be aligned using beam derived information
- Tolerance corresponds to roughly 100 μm 'dispersion' error (dispersion is not exact in linac with varying energy spread)
  - With 1 μm BPM resolution, 100 μm dispersion not so bad!
- Desire very local correction (align every quadrupole perfectly) with a procedure that does not interrupt luminosity
  - Measuring quadrupole center shifts at SLAC and FNAL
  - Find <1μm motion in EM quads but larger in PM quads
  - Investigating alternate routes (DF steering, ε-bumps, ballistic corr.)
  - Thinking about beam tests



FFTB Quadrupole Alignment

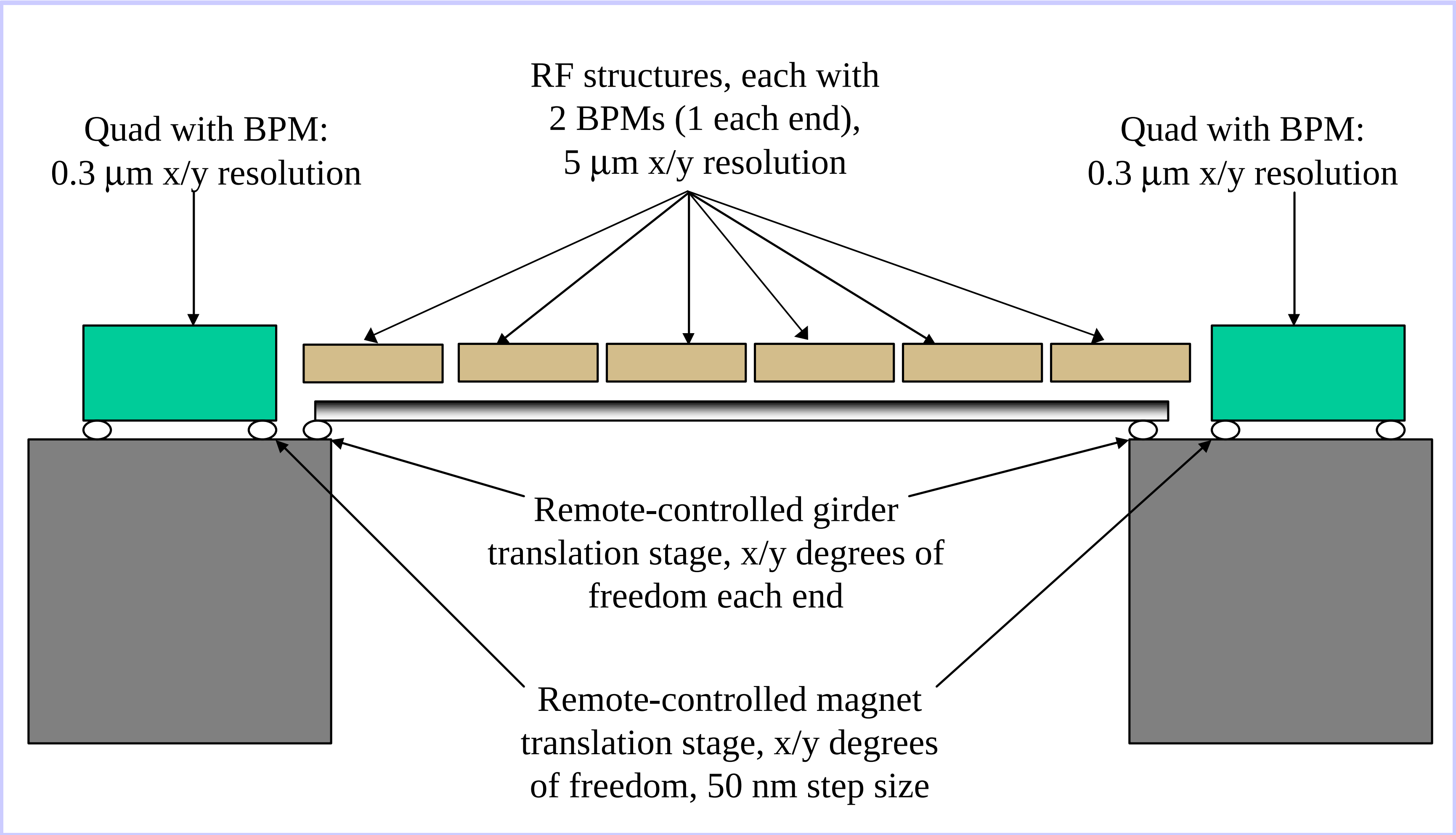
- Used quadrupole shunting technique
  - Fit residuals ranged from 2 µm to 30 µm at the end of the beam line
    - FFTB optics poorly designed for beam-based alignment
    - Ran out of BPMs to measure deflected trajectory!
  - Dispersion measurements show errors in 1st two regions < 7 µm after alignment
    - Confirms technique
  - NLC designed for BBA with better diagnostics and smoother optics
    - Would expect a factor of 2 ~ 3 improvement
  - TESLA has poorer ratio of tolerance to diagnostic res.



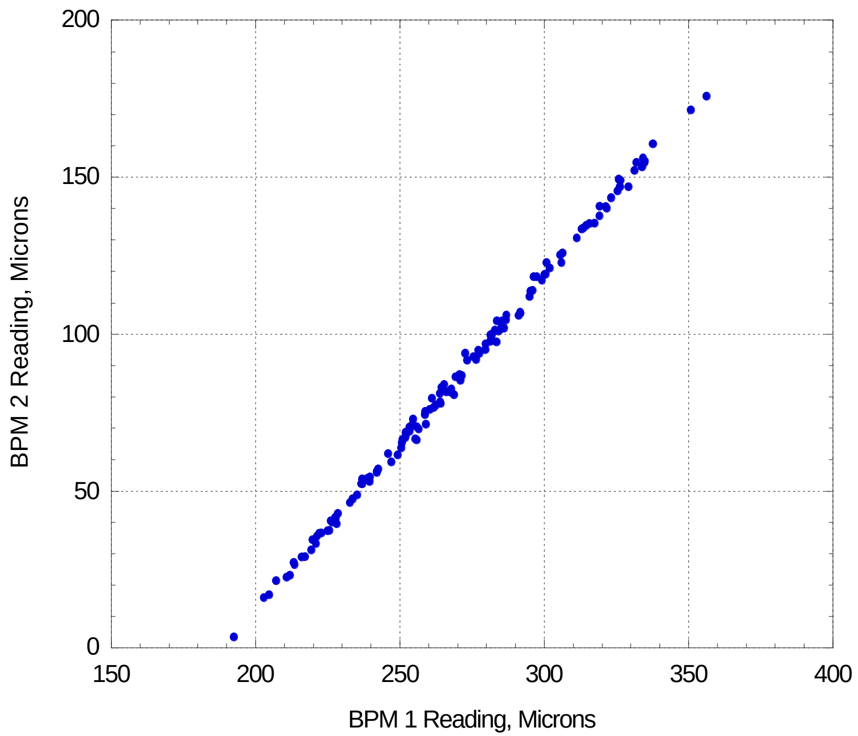
Alignment Procedure in NLC

- Conventional alignment at installation and after long downs
  - 100 μm rms variation of magnets and girders over 100 m lengths
- Establish 'gold' trajectory using local and/or quasi-local correction techniques
  - Quadrupole shunting techniques align BPMs to quadrupoles at the level of 1 to 20 μm depending on **variation of quadrupole centers**
  - Dispersion-Free steering to establish a **'gold'** trajectory which minimizes the dispersion - need to correct η to 100 μm level
- Steer to 'gold' trajectory as magnets move (few hr timescale)
  - Use feedback to maintain trajectory between steering
- Beam-bumps to tune emittance based on emittance meas.
  - Ideally create 'dither' feedback to tune emittance bumps

Beam-Based Alignment and Steering Equipment



Position Monitor Resolution

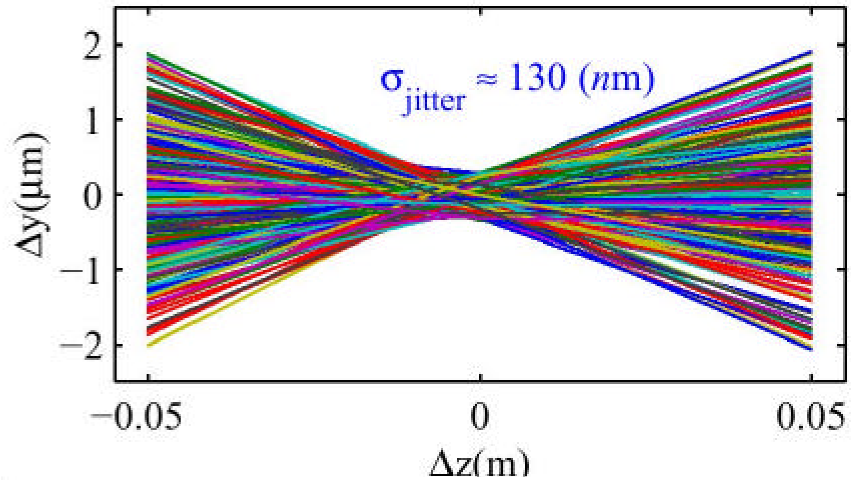


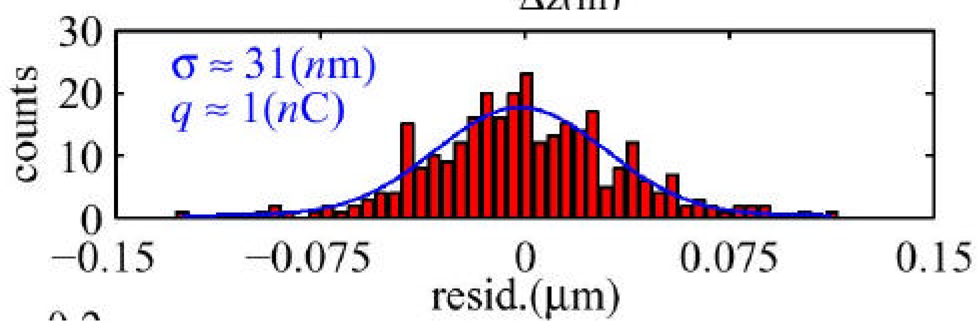
FFTB Stripline BPMs:
1 μm resolution @ 10^{10} / bunch

Need factor of 3 better for NLC

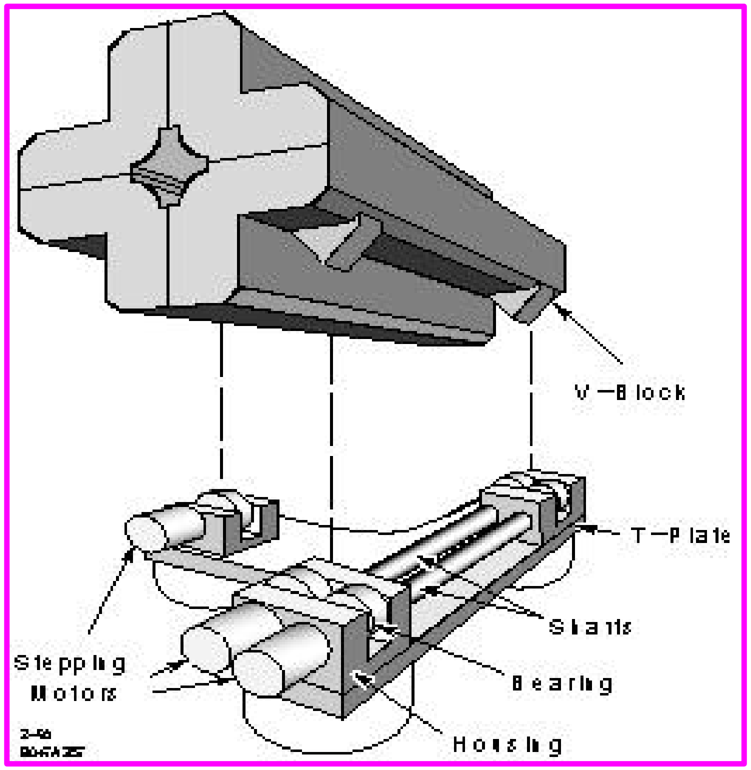
FFTB Cavity BPMs:
25 nm resolution @ 6 x 10^9 / bunch

Present NLC baseline uses cavity BPMs in main linac

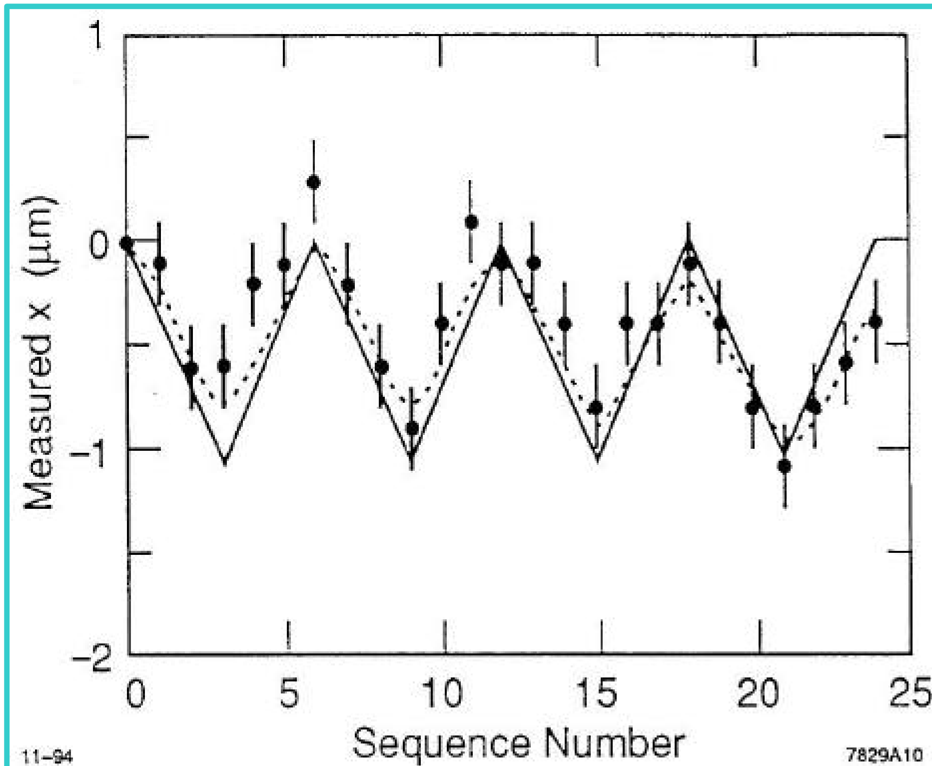




Mover Resolution



Test of FFTB Magnet Mover Single Step performance: expected (solid) laser interferometer (dashed)



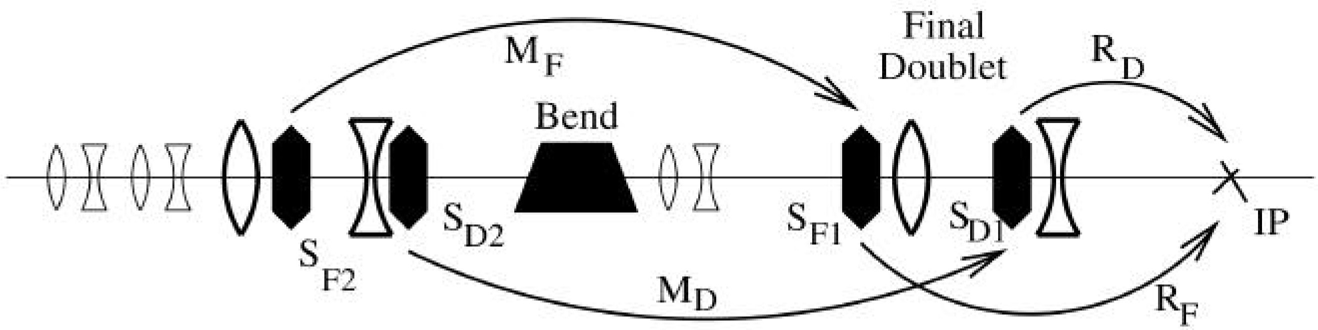
FFTB Magnet Mover:

0.3 µm step size

Need factor of 6 better -- attainable with micro-stepping technology

Beam Delivery Systems

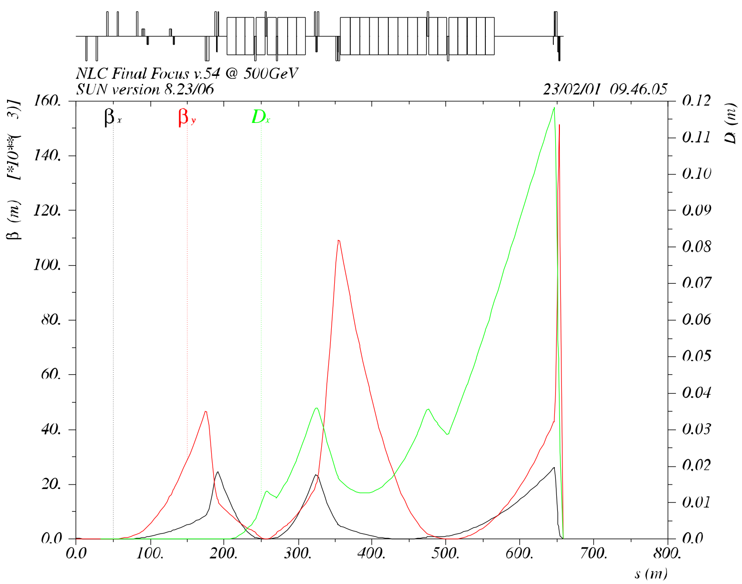
- New final focus system has a much more compact design

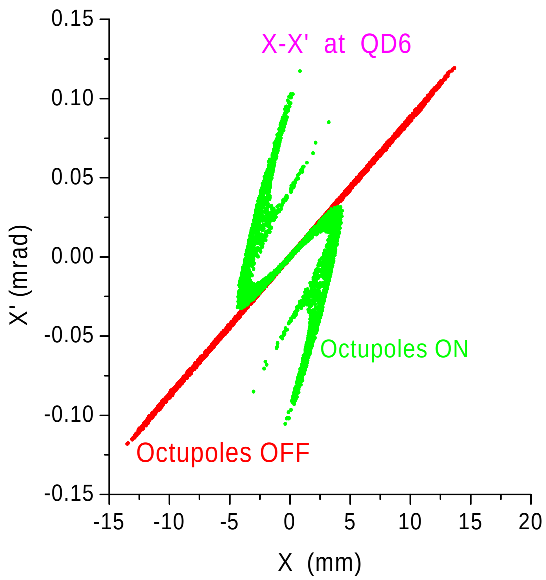


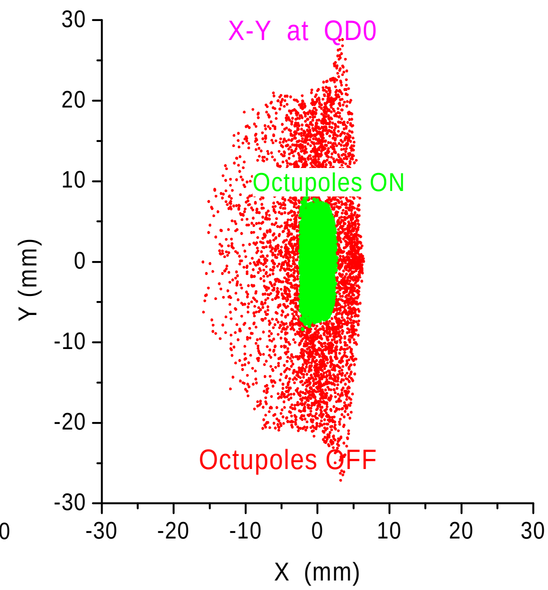
  – Final Doublet is required to provide the necessary demagnification
  – Chromaticity is cancelled <u>locally</u> by two sextupoles interleaved with the FD, a bend upstream generates dispersion across FD
  – Geometric aberrations of the FD sextupoles are cancelled by two more sextupoles placed in phase with them upstream of the bend
- System adopted by NLC and CLIC – TESLA considering

Advantages of New FF

- New FF is only 700m for 2.5 Tev beams
- Longer L* ~ 4 m to ease detector integration
- Smaller aberrations reduce tail generation
- Octupole doublets focus in both planes simultaneously

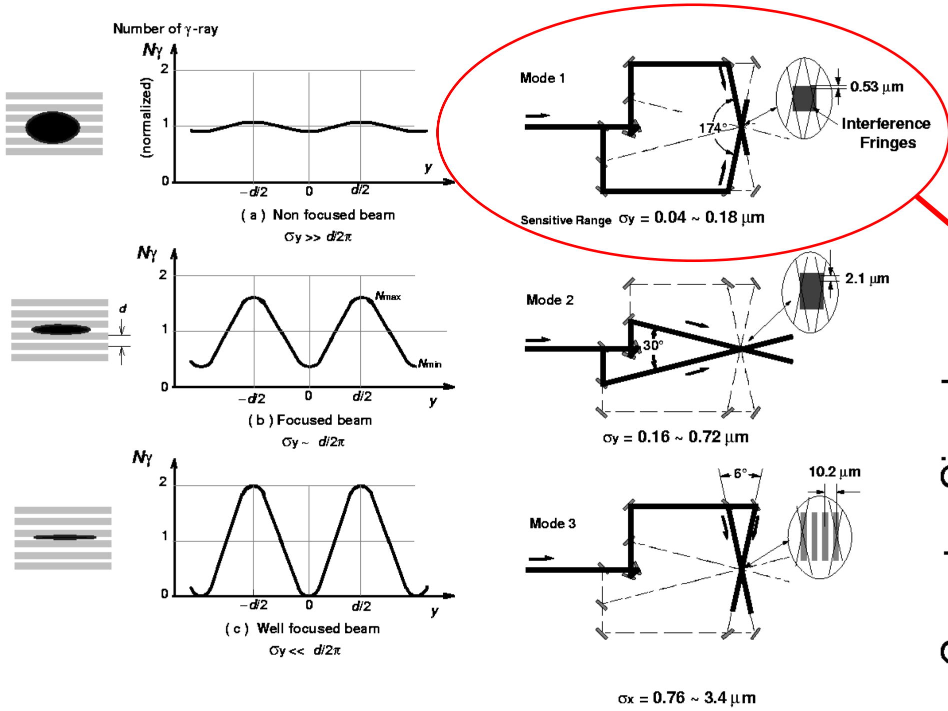






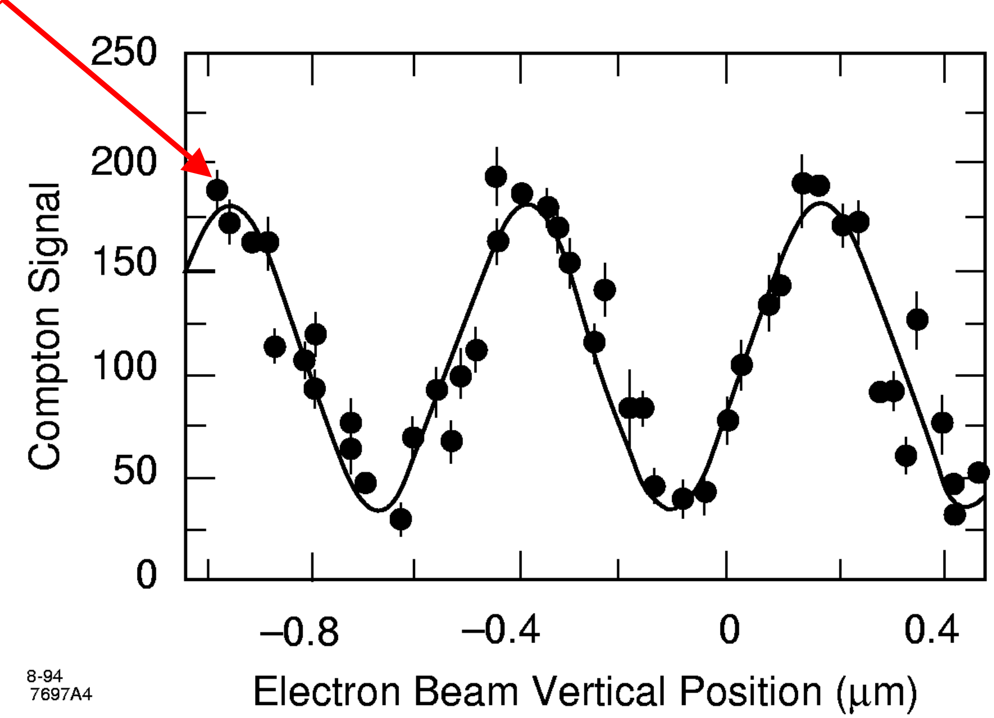
FFTB

Principle:



Typical Measurement:

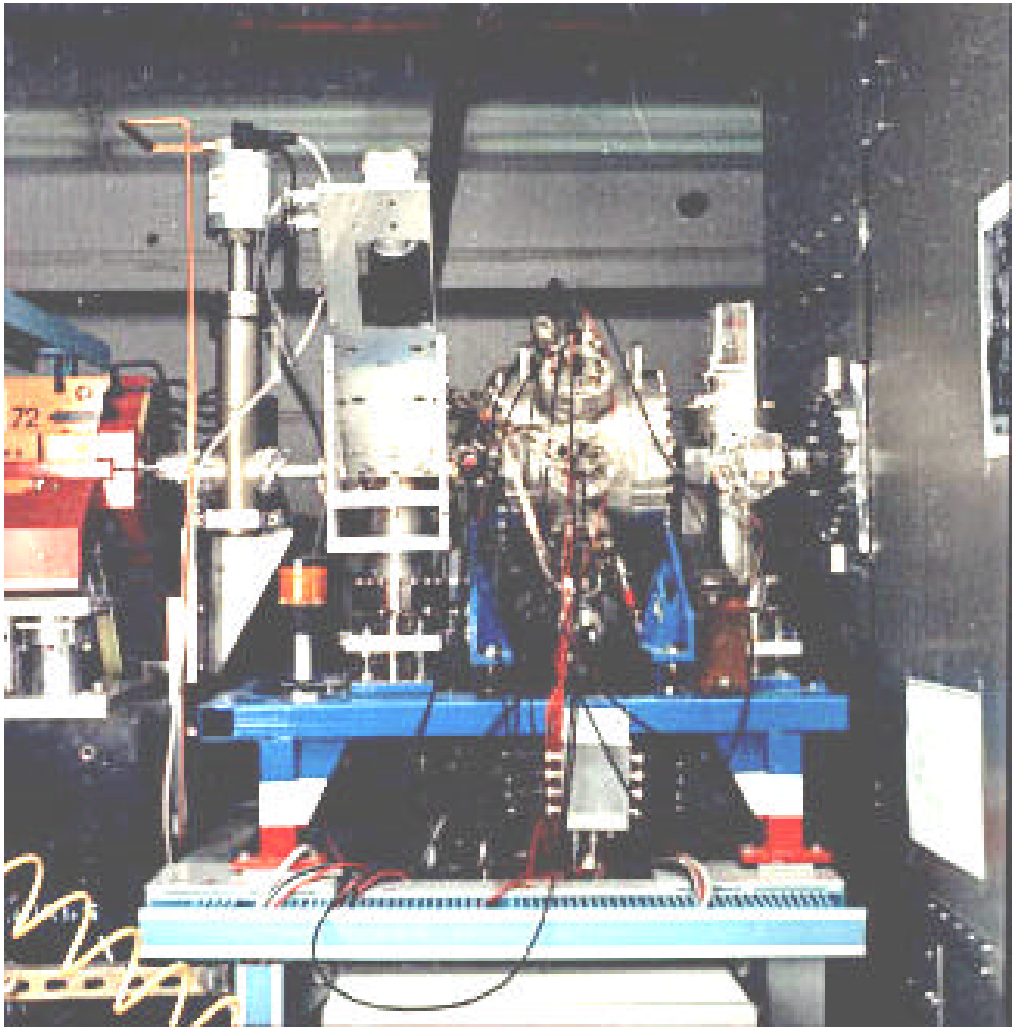
$s_y = 77 \pm 7$ nm



Laser-Interferometer Beam Size Monitor

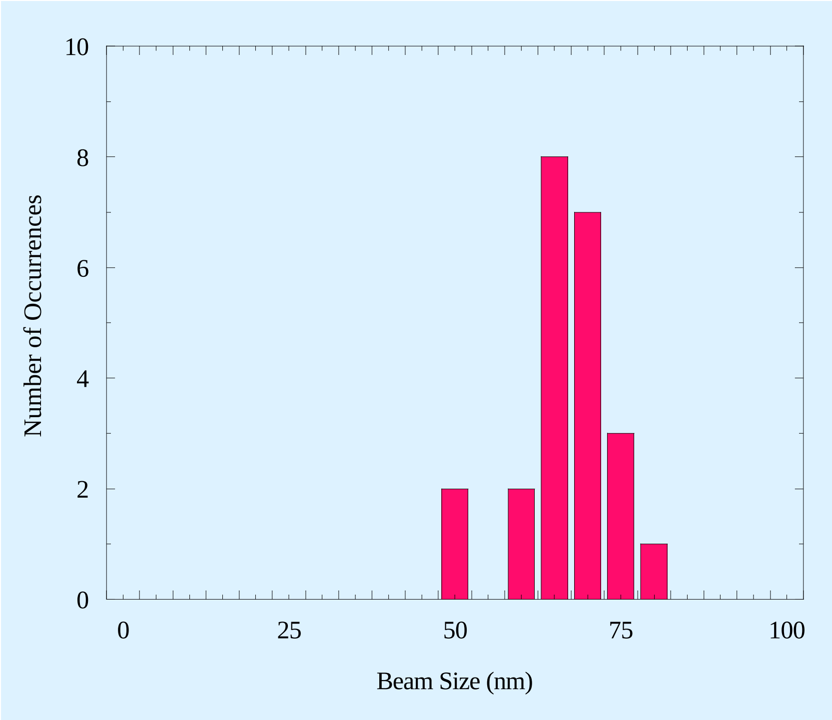
Final Focus Test Beam at SLAC

FFTB IP

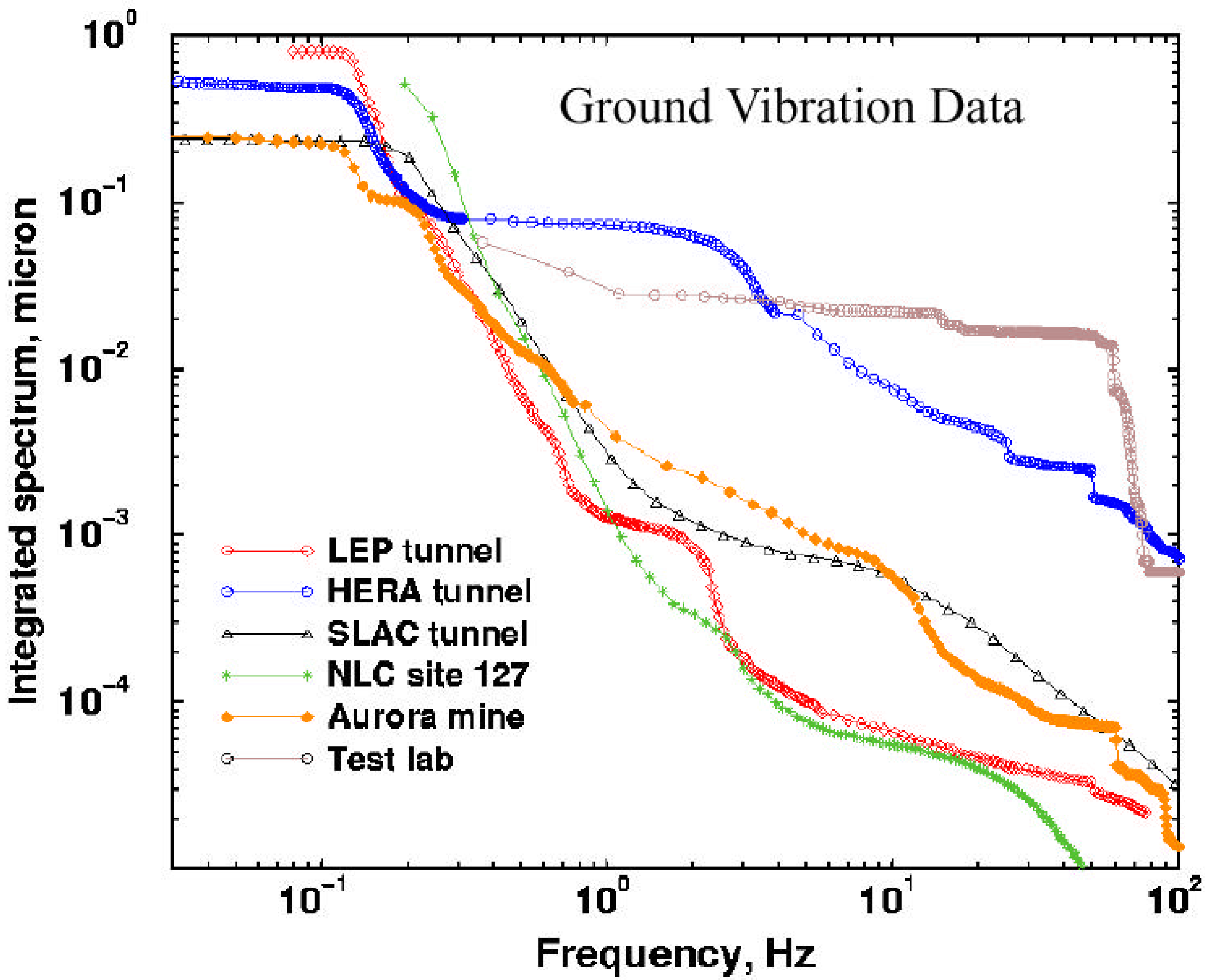


FFTB measured vertical beam size of 60-70 nm at IP with laser interferometer

Demonstrated precise diagnostics!

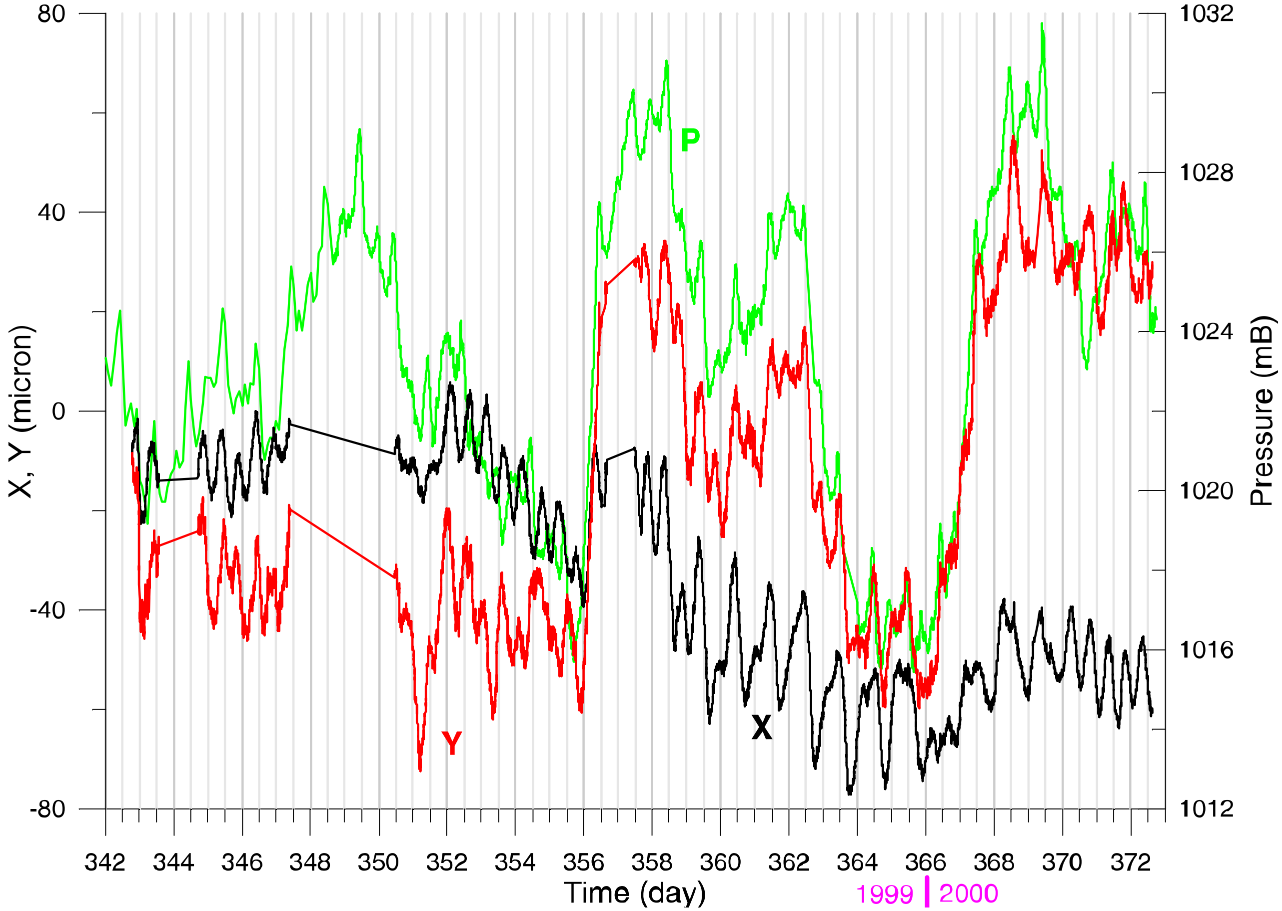


Ground Vibration Data



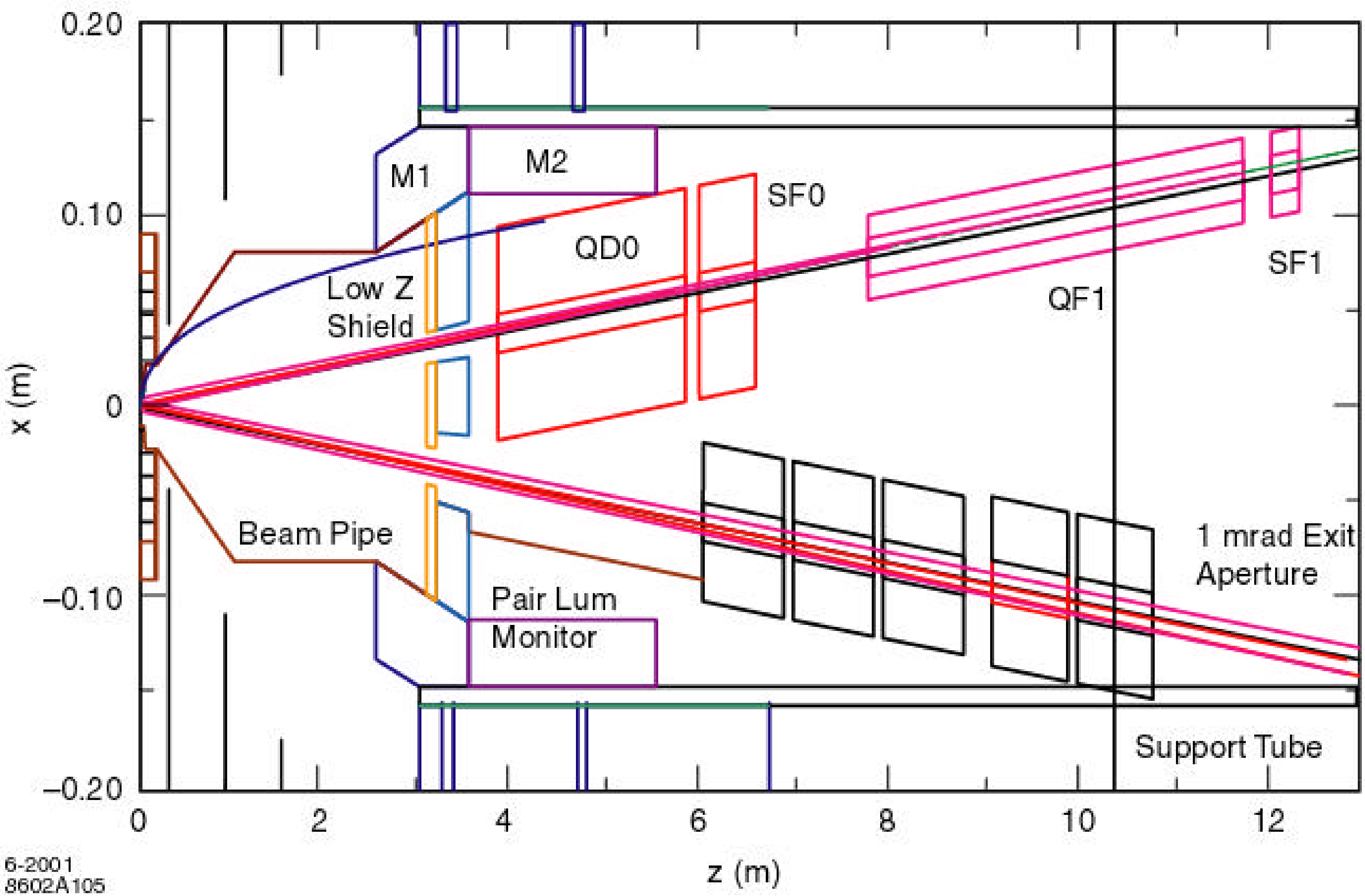
SLAC Tunnel Drift Studies

- Motion has strong correlation with external atmospheric pressure and tides
- Correlation seen between ground characteristics and slow motion
- These slow motions are OK



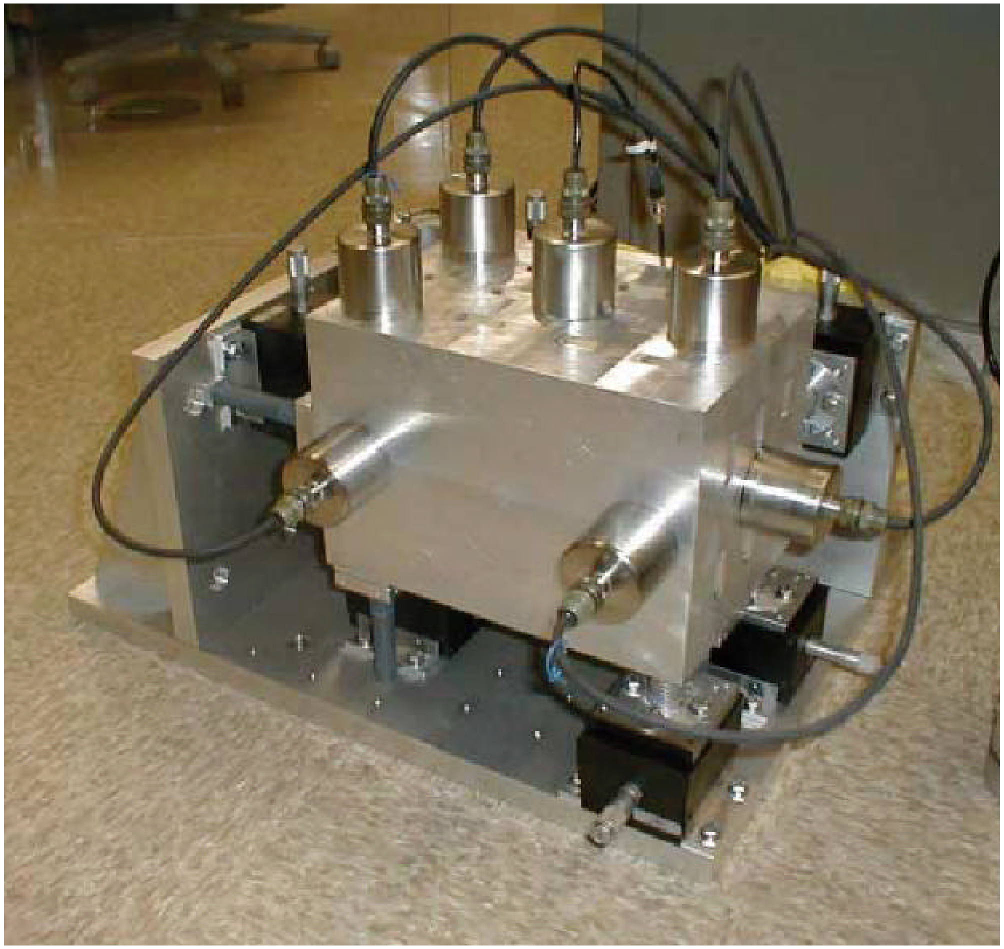
Horizontal and vertical displacement of the SLAC linac tunnel and external atmospheric pressure from Andrei Seryi

NLC IR Layout

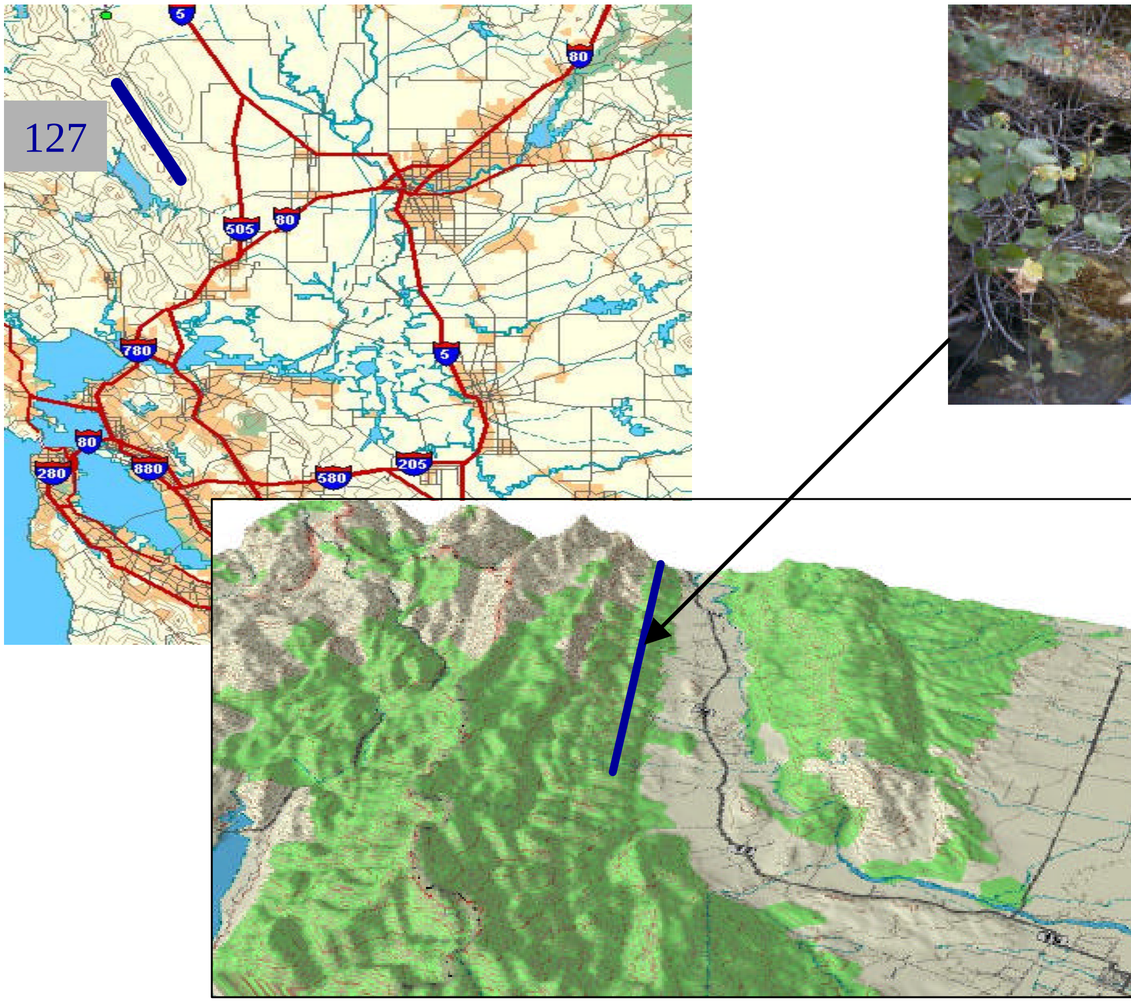


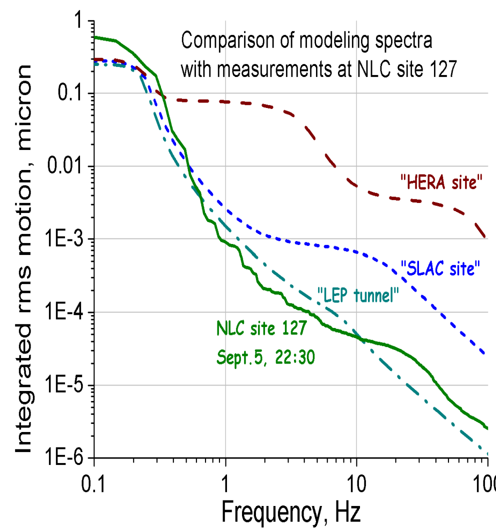
Stabilization

- Typical vibration tolerances are 1000x tighter than alignment tolerances ~ 10 nm
- Vibration tolerance on final focusing magnets is ~1nm
  - Must stabilize these components!
  - Two approaches:
    - Optical anchor (tie elements to bedrock with an interferometer
    - Inertial stabilization

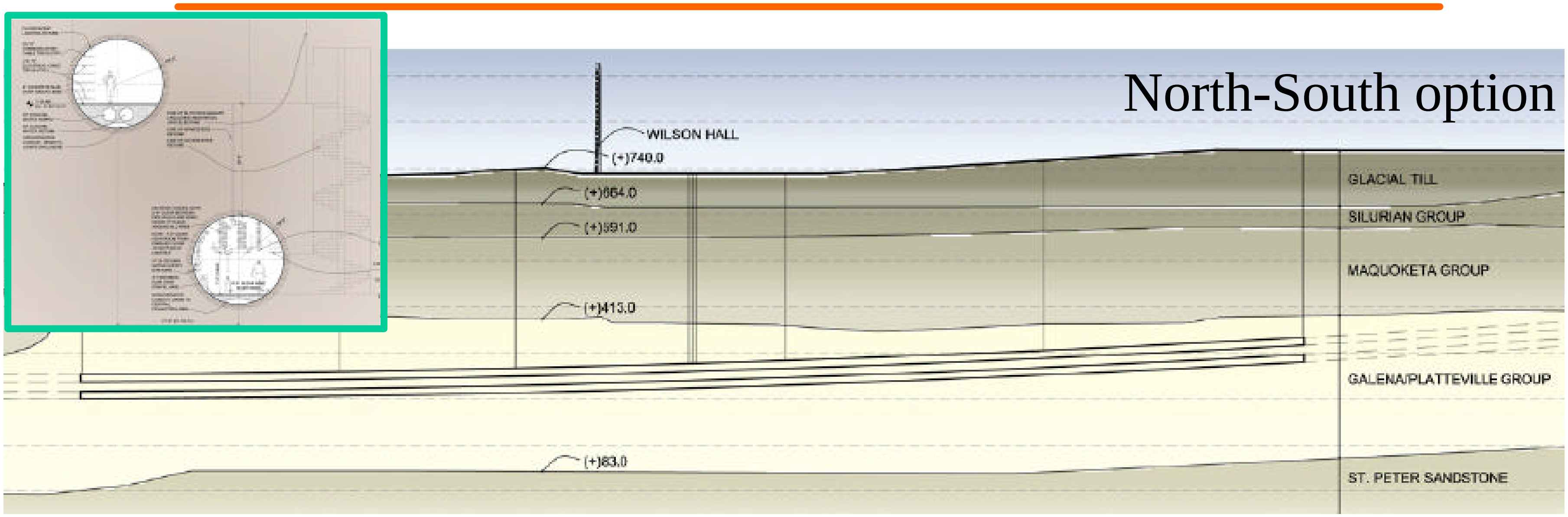


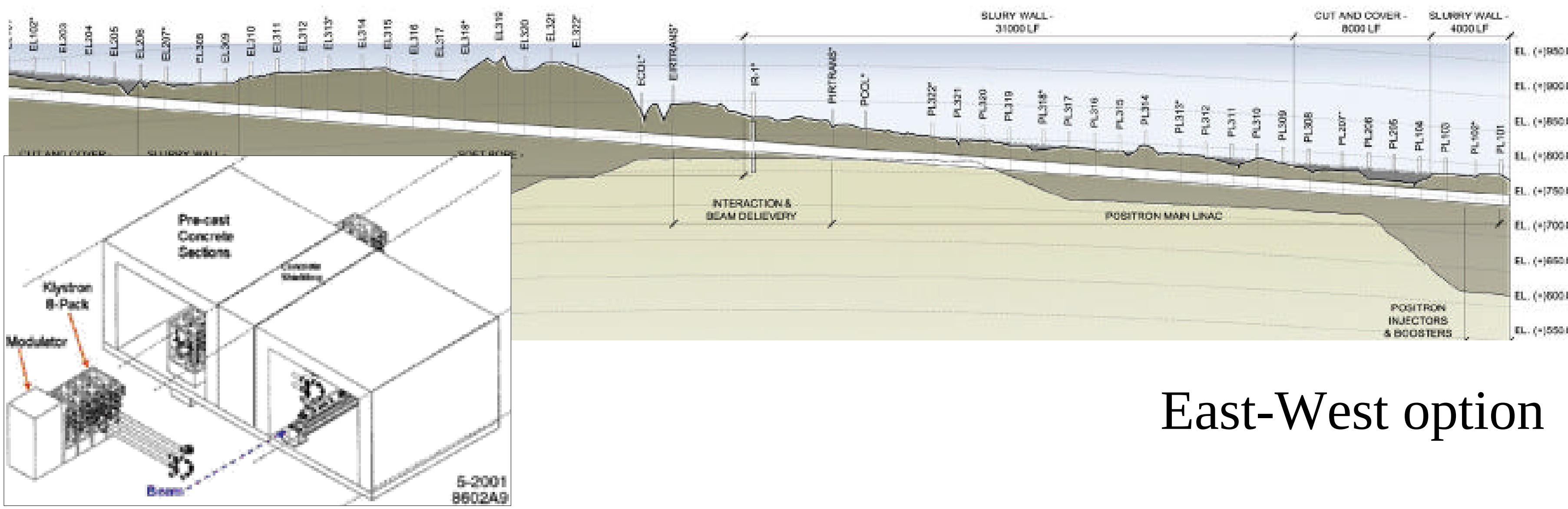
Possible California Site Option





Possible Illinois Site Options





East-West option

Reliability Issues

- Essential to understand!
  - Significant limitation in SLC operation
    - Would take 3 ~ 4 times the length of each down time to recover luminosity!
- New LC are being designed to avoid known problems
  - Multiple (redundant) power supplies
  - Overhead in klystron / modulator populations
  - Redundant electrical / cooling systems
  - Big questions regarding TESLA single tunnel with accesses/10 days
    - Radiation levels have only been checked at 17 MV/m (turned off 1 cavity)
    - Operation model based on 40,000 hr klystron lifetime – only operated for ~2000 hrs at 25~40% power and 1 Hz
    - Modulator cables; temp stability; low level rf electronics
- Must qualify reliability of all components, especially those in the tunnel!

International Milestones

HEPAP

– The United States …
  - Strong recommendation in Sub-Panel Report.
  - The "New Reality" in Washington since September 11.
  - DOE, NSF, OSTP will be testing support of broader science community.
  - U.S. Linear Collider Steering Group.

ECFA

– German Wissenschaftsrat reviewing TESLA along with other major physics initiatives (e.g. European Spallation Source), and expected to report in Summer 2002.

ACFA

– Japanese (KEK) will submit request for JLC Project Preparatory funds (rough equivalent of U.S. Conceptual Design) in Fall 2002. Monbusho must weigh against other initiatives (e.g. ITER).

ICFA

– Loew Committee compilation of design and R&D at EPAC in Paris in June 2002.

– International steering group to be formed

2001 ICFA Technical Review

- Compare four projects: CLIC, JLC (C), NLC/JLC (X), TESLA
  - 1) Whether any or all of these four approaches can lead to a functional project with the required design and operating parameters,
  - 2) Further R&D that is required

ILC-TRC Steering Committee

Chair:	Gregory Loew (SLAC)
Members:	Reinhard Brinkmann (DESY)
	Gilbert Guignard (CERN)
	Tor Raubenheimer (SLAC)
	Kaoru Yokoya (KEK)

- Form two working groups:
  - Energy (primarily rf technology but include reliability and upgrade routes)
  - Luminosity (try to evaluate the real luminosity potential)

- Present draft at the European Particle Accelerator Conference, June 2002

Summary

- NLC rf system is making great progress
  - Rf systems for 500 GeV cms is close to being ready
    - Need to test final prototypes for modules, HOM damping, couplers or pulse compression, and klystrons
    - Need to gain operational time at nominal gradients
  - Rf cavities for 1000 GeV cms will probably be ready in 2003
- Luminosity issues are a larger concern!
  - Damping rings are essential for stable operation
    - Lots of potential problems – still largely not understood
  - Both linear collider designs require complicated BBA procedures
    - FFTB and SLC developed instrumentation and techniques necessary for beam-based alignment
  - Vibration of final doublet requires active stabilization
  - Beam-beam effects are significant and may force reduction in luminosity in both designs